

Advanced Organic Composite Materials for Aircraft Structures— Future Program

Committee on the Status and Viability of Composite
Materials for Aircraft Structures
Aeronautics and Space Engineering Board
Commission on Engineering and Technical Systems
National Research Council

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Preface

At the request of the National Aeronautics and Space Administration's Office of Aeronautics and Space Technology, the National Research Council's Aeronautics and Space Engineering Board established a committee to undertake an examination of the status of advanced organic composite material for aircraft structures. The committee's tasks were to assess the state of this technology and to identify the research and technology development actions that would assist in the acceleration of the application of this material in production aircraft.

The tasks of the committee were accomplished through deliberations following a series of reviews of government and industry experience and activity, and committee discussions of benefits, inhibiting factors, technology development needs, and possible government action. The work of the committee is summarized in the body of the report, which provides background related to the field of organic composites and of this study, including the approach used by the committee to exercise its task. These chapters of the report are followed by brief discussions of the committee's findings and recommendations. The report itself is supplemented by summaries of the work of the committee related to their views on benefits and technology needs, government agency dialogue on issues, questions and technology needs, and a synopsis of the presentations made to the committee. These materials were used to develop the findings and recommendations presented in the report.

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Introduction

Revolutionary advances in structural materials have been responsible for revolutionary changes in all fields of engineering. These advances have had and are still having a significant impact on aircraft design and performance. Early aircraft construction involved wood, fabric, and wire, which later gave way to metals, notably aluminum. Aluminum has given way to selected use of other higher-strength metals (titanium, steel, and superalloys), and both are giving way, to a significant degree, to composite materials.

Composites are engineered materials. Their properties are tailored through the use of a mix or blend of different constituents to maximize selected properties of strength and/or stiffness at reduced weights. A common composite approach is to use a matrix or host material reinforced by a fibrous second material. These composites can be ceramic, polymer, or metal based, or mixtures of these materials. Of special interest in this study are filamentary (organic) polymer systems, herein commonly referred to as advanced organic composites.

More than 20 years have passed since the potentials of filamentary composite materials were identified. In a report dated July 1964, the Scientific Advisory Board of the U.S. Air Force recommended the intense development of boron filaments. The board identified significant gains in aircraft weapon-system performance through application of boron composites because of their low densities and high strengths and stiffnesses per unit of mass.

During the 1970s, however, much lower-cost carbon filaments became a reality and gradually designers turned from boron to carbon composites. By 1971, there was so much unfettered enthusiasm for carbon epoxy that 16 suppliers were marketing over 50 brands of carbon-epoxy preimpregnated (prepreg) materials. The boron-epoxy material system was developed with substantial assistance and direction from the government through the Air Force Materials Laboratory, but the carbon-epoxy material system received only limited government assistance and direction.

The list of composite achievements over the past two decades is long and impressive. Two high-performance military airplanes, the F-18 and AV-8B, currently in production, utilize carbon-epoxy for 10 percent and 26 percent of their structural weight, respectively. These carbon-epoxy percentages include appreciable portions of the primary structural elements of the wings, empennages, and control surfaces of these aircraft. Two new transports, the Boeing 757 and 767, each use about 3,000 pounds of carbon-epoxy in rudders, elevators, and spoilers. Two aircraft under development, the U.S. Navy Osprey V-22 and the Beech Aircraft Starship, merit the appellation "all-composite" because nearly all of the structural components that can gainfully use composites are made of composites.

Despite these and other examples, filamentary composites still have significant unfulfilled potential for increasing aircraft productivity; the rendering of advanced organic composite materials into production aircraft structures has been disappointingly slow. This report addresses why and recommends research and technology development actions that will assist in accelerating the application of advanced organic composites to production aircraft.

Study Charter and Methodology

Late in 1985, the Aeronautics and Space Engineering Board of the National Research Council, at the request of the National Aeronautics and Space Administration's (NASA) Office of Aeronautics and Space Technology, formed a committee that was chartered to assess the status and viability of organic composite technology for aircraft structures. The charter directed the committee to concentrate on advanced organic composites. The committee was to make recommendations concerning ways that federally sponsored research and technology development programs could produce a more rapid and timely translation of the potential of these composites into production aircraft. The committee responded to this charter by:

1. Reviewing pertinent government aircraft application, design, production, and service experience with advanced organic composites. Agencies included NASA, the Federal Aviation Administration, and the U.S. Army, Air Force, and Navy.
2. Conducting a forum at which aerospace engineers from prominent design, manufacturing, and operating industrial segments (transports, airline operators, rotorcraft, high-performance aircraft, general aviation, and material producers) presented their views on status, viability, future applications, and technology development needs.
3. Reviewing ongoing federal research and development programs and the perceptions of the various government agencies of issues germane to future applications and technology development program needs.
4. Conducting a workshop to assess critically the data and opinions amassed during steps 1, 2, and 3 and to prepare an outline and a rough draft of this report.

The committee arrived at its findings and developed recommendations through an examination of the following aspects of advanced organic composite material technology:

- Potential benefits
- Inhibiting factors
- Needs for technology development
- Possible government actions

The committee found it convenient to partition the "universe" of this study into the following elements:

- Large transports
- Rotorcraft
- High-performance aircraft
- General aviation

as well as

- Materials
- Airline operators

A summary of the committee's examination of these complex matters is presented in the report's Supplement. The Supplement has two parts: (1) Program Assessment; and (2) Response to Government Issues and Questions. A Synopsis of Presentations to the Committee is presented in Appendix A. The committee arrived at its findings and recommendations through deliberation and its workshop activity.

Discussion and Findings

AIRCRAFT DIFFERENCES

There are appreciable differences in the structural requirements and usage of the four classes of aircraft addressed: large transports, high-performance military aircraft, rotorcraft, and general aviation aircraft. Large commercial transports are designed to a limit-load factor of 2.5 g, compared to 9 g for high-performance military aircraft. Large commercial transports fly 10 or more hours a day and experience thousands of takeoffs and landings through their lifetime. As a result their pressurized fuselages experience loads approaching limit load thousands of times. High-performance military aircraft fly only 20 to 40 hours a month during peacetime and reach or exceed limit load relatively few times—in the hundreds—during their lifetime. The design longevity of a transport is upward of 40,000 flight hours whereas high-performance military aircraft have a design life of some 6,000 to 8,000 flight hours.

Rotorcraft, both military and civil, are designed for relatively low limit-load factors of 2.5 g to 3.0 g and are often flown at or close to these limits. The rotorcraft design problem is complicated by the wide spectrum of vibratory loads imposed by different speed regimes and associated design limitations as well as the high degree of maintenance required.

General aviation aircraft, the Federal Aviation Administration's (FAA) category for aircraft whose takeoff gross weight is under 12,500 pounds, are lightly loaded and are maintained by an infrastructure that is much different from large transports or military aircraft. Their structural design is dominated by stiffness rather than strength.

These factors as well as others lead to structural configurations and design detail that are unique for each of the four classes of aircraft. Thus, for example, it is

basically not practical to scale up geometrically a general aviation aircraft into a large transport or vice versa. Despite these differences, there are similarities in the potential benefits, inhibiting factors, needs for technology development, and possible government actions with respect to advanced organic composite material research and technology.

MEASURES OF PERFORMANCE

Range and maneuverability are two of the traditional measures of aircraft performance. The benefits of a lower structural weight fraction are quantified by the Breguet range and specific excess-power equations. Both of these equations contain only aircraft performance variables. For example, the Breguet equation will show either the increase in range attendant to reduced structural weight for the same gross-weight airplane or the same range for an airplane of less gross weight.

Previous advanced composite research, technology, and development programs have focused on improvements in these kinds of aircraft performance parameters. Neither the Breguet range equation nor the specific excess-power equation addresses improved aircraft system capability. Here, for example, structural weight savings can be used for increasing mission capability, such as adverse weather flight, wind-shear warning, collision avoidance, category 3 landings, and air-freight adaptation, and for modifying military aircraft with equipment to cope with increasingly sophisticated enemy defenses. Thus, more and more avionics are being put into all classes of airplanes.

Structural weight savings for future military aircraft can be expected to allow multipurpose capability; for example, the same basic airplane could be called upon to fulfill attack, air defense, and interdiction missions. Additionally, stealth, a future requirement, places special demands upon the application of organic materials. For civil aircraft, structural weight savings can be translated into reduced direct operating costs resulting in lower passenger seat-mile or cargo ton-mile costs.

Structural integrity directed at providing greater absolute safety is another evolving factor that requires increased attention to design detail. An example is the recent addition of the damage tolerance concept to the federal aviation regulations. This new regulation could result in more structural weight as well as many more engineering hours for design and testing.

These aircraft system requirement trends tend to increase takeoff gross weight, although the traditional performance requirements (measures), such as range, takeoff distance, altitude, and cruise speed, remain the same or call for improvements. Unless new technology is forthcoming, these more capable aircraft will be larger, heavier, and require more propulsive power, thereby becoming less productive. It is for this reason that advanced composites of all kinds—metals as well as organics and combinations—have a unique future role. They can provide the designer with the ability to reduce structural weight significantly, allowing the addition of safety and operational improvements while holding aircraft to reasonable sizes and gross weights.

ADVANCED COMPOSITES AND ADVANCED STRUCTURES

Advanced composites coupled with various, possibly new, structural concepts will further reduce the structural weight fraction of the airframe. The enhanced reductions can then be used by designers to provide aircraft system improvements beyond those available through material improvement alone.

New, higher-performing aircraft will be smaller and more productive for the same mission. At a minimum, for example, these aircraft will takeoff and land from the same airports or aircraft carriers, use the same gates at airports, cruise at the same altitudes, and have the same or greater operational capability. For the same gross weight, they will have greater range and/or operational flexibility. Through new design with lower structural weight, they may be able to perform entirely new missions.

Cost Issues

Every constituency (transport, fighter, rotorcraft, and general aviation) and every government agency (NASA, Army, Air Force, Navy, and FAA) listed cost as a major inhibiting factor to the more widespread application of advanced composites. Early in the development of advanced composites, system "effectiveness" was promulgated as the justification for using a material that cost \$100 or more per pound. Aluminum alloys could be purchased for \$1 or \$2 per pound.

Although significant reductions in cost have been realized, there is still an order-of-magnitude difference in the cost of carbon-epoxy compared to aluminum. Some consider material cost not a dominant cost factor. However, material cost is important in commercial aircraft and a concern in military aircraft. At present, cost issues run the gamut from materials to certification, tooling, and other facets of manufacturing as well as the retraining of engineers and shop personnel whose expertise is in metal technology.

Manufacturing costs are identified as a significant cost. This involves not only the placement but the distribution and processing of material to optimize manufacturing from cost considerations.

While grappling with the wide range of issues associated with costs, the committee noted that many people believe that costs play a dominant role in the selection of the technology used in a new aircraft design. There is some concern that system costs have been used as an argument for inaction, both with respect to the development of advanced composites and the development of new airplanes using composites.

If all other factors were the same, lower costs alone would encourage the fuller use of advanced composites. But these factors are not the same. The committee found other significant technical inhibitors to the use of advanced composites, inhibitors that can be overcome by basic research and technology development.

Other Inhibiting Factors

Presently, designers cannot design complete composite structures with the same

level of confidence with which a metal structure can be designed without planning for extensive testing. The composite designer has neither the comparable metallic data base nor methodology to address fully such structural integrity factors as strength, longevity, damage tolerance, lightning strikes, and durability.

There is extant a very large investment in machine tools to fabricate metal components as well as a work force with years of experience in "cutting" metal. The lack of an engineering data base in conjunction with an immature manufacturing capability tips the scale toward metal technology and/or forces designers to be so conservative that the true potential of advanced composites is not realized. Also, the owners/operators of composite aircraft have concerns with respect to serviceability, maintenance, and repairability because of the relatively narrow service experience with advanced composites.

Government R&T Role

The committee recognizes the need for tough budget decisions. These decisions, in particular, have adversely affected the levels of funding available to NASA and the other government agencies for their aircraft structures' advanced organic composite research and technology development (R&T) activity. The result, in the view of the committee, has been a general sense of drifting in the NASA program resulting, in particular, in a loss of R&T program leadership. The committee believes the nation cannot afford this loss. There is an important role for NASA and the other government agencies to play in providing resources for needed R&T, in coordinating the attack on the factors that inhibit the beneficial application of composites and in assisting the United States in retaining a leadership role in aeronautical systems development and sales.

Regarding the role of government in future technology development, the committee agrees with earlier studies that the government has a vital role in aeronautical R&T, including advanced composite material for aircraft structures.* This unique role stems from the importance of aeronautics R&T in social, economic, and defense affairs and from the diverse nature of the industry itself. Industry cannot provide (and cannot be expected to disseminate among itself) the technology developments needed in industry for design, development, and manufacture, and by government user agencies (U.S. Department of Defense and FAA) for advanced aircraft system specification, definition, and certification.

The advanced composite material R&T addressed in this report has been identified as important to aeronautical developments through the year 2000 and beyond.^{13,15} It is particularly important to the first of the three major aeronautical R&T policy areas (subsonic, supersonic, and transatmospheric) identified by the President's Office of Science and Technology Policy (OSTP)^{1,14,17} in their studies

*See items 1, 9, 12, 13, 14, 15, and 17 in the bibliography listing. The following document, published after the work of this study was completed, also relates to the role of government in research, technology, and development: "National Aeronautical R&D Goals: Agenda for Achievement," Executive Office of the President, Office of Science and Technology Policy, Washington, D.C., 1987.

of aeronautical R&T policy. The subsonic goal (to which most of the committee's comments apply) identified by OSTP notes that the United States should

Build trans-century (civil) renewal through new technology, affordable aircraft, a modernized air space system, and key technology advances for 1995 readiness. This activity will support military aircraft development and supersede foreign technology challenges.

Although the committee did not address the details of a possible R&T program, the committee firmly believes that the appropriate government agencies should do so, led by NASA. The effort should be aimed at understanding the fundamental knowledge needed to build composite aircraft structures for the twenty-first century. This planning, of course, must include consideration of advanced metals and metal-composite mixes.

FINDINGS

In summary the committee has arrived at the following major findings:

1. *Technology Maturation*—Advanced organic composites need to proceed through a technology maturation phase that includes manufacturing. The technology has reached an application plateau far below its potential height. An order-of-magnitude increase in resources devoted to the development of basic knowledge, requiring both analyses and experiments, is justified, in the view of the committee, on the basis of the aircraft performance and cost gains to be realized.

2. *National Need*—The sale of aircraft is presently the major contributor to a positive balance of payments for industrial products, but foreign competition is becoming stronger. Looking to the year 2000, aircraft primary structural weight can be reduced by some 20 to 25 percent and possibly by as much as 50 percent compared to an all metal structure. Costs can also be reduced by this magnitude, providing the United States with a competitive posture in aircraft sales against strong and growing foreign competition.

3. *Technology Potential*—Advanced organic composites are an enabling technology for achieving the nation's subsonic goal of transcentury leadership in subsonic aircraft. This is a primary technology for allowing significant reductions in structural weight fraction.

4. *Weight-Saving Implications*—Applications of advanced organic composites have verified the predictions of lower structural weight, and the performance advantages of reduced structural weight have been demonstrated. Advanced organic composites have been and will continue to be used to improve aircraft range and takeoff gross weight through weight saving. A lighter structure permits the addition of fuel for greater range or airplane downsizing to achieve the same range and payload or to allow new capability.

5. *New Capability*—The unique characteristics of advanced organic composites make it possible to build new types of aircraft such as highly maneuverable, high altitude, vertical and short takeoff and landing vehicles and enabled the realization of the around-the-world Voyager, which, in all probability, if constructed of metal

would not have useful range and payload. The ability of the designer to tailor structural properties, for example, makes possible the design of structurally efficient forward swept wings while avoiding serious aeroelastic problems, and to fabricate unique structural shapes and configurations. Organic composite material may offer an opportunity for enhancing the low observable characteristics of military aircraft.

6. *Flight Safety*—Greater flight safety can be achieved by using some of the reduction in structural weight fraction to increase current levels of structural crash-worthiness and to accommodate increasing amounts of avionics for providing such capability as blind landing, collision avoidance, wind-shear warning, and fault tolerant control.

7. *Productivity*—Greater productivity is also possible for civilian and military aircraft. For the military, the structural weight reduction can be used to increase payloads, whether passengers or cargo, for transport aircraft, or to allow an aircraft to serve dual functions—air superiority and attack.

8. *Lower-Cost Manufacturing*—There is the potential, while largely unproven, of significant cost gains through low-cost manufacturing using such techniques as filament winding, protrusion, and hot forming, as well as integrated-structure fabrication of fuselages and wings. Reduced costs here will remove an application barrier and enhance the competitive position for U.S. aircraft.

9. *Support*—Issues pertaining to maintenance, serviceability, repairability, and supportability will require continuing diligence but do not appear to be insurmountable. There are some nagging concerns about repair, nondestructive evaluation techniques, and environmental effects, but the recommended R&T should help allay and resolve these concerns and lead to an improved ability to apply composites.

10. *Inhibiting Factors*—A partial list of factors that inhibit the more aggressive application of advanced organic composites, and need to be resolved, are:

(a) a *small data base*, much smaller than available for metals, e.g., there is no document comparable to MIL Handbook 5 for composite materials due to the difficulty of producing appropriate data. In general, the design data base must be larger for composites due to material anisotropy and the lack of well-defined failure theories.

(b) the *relative lack of knowledge of the behavior of mechanically fastened joints*,

(c) a concern in some quarters about the *lack of reliability of bonded joints and sandwich construction*,

(d) a much *less complete and poorer understanding of fracture and failure modes and behavior under cyclic loads*, especially for rotorcraft, e.g., there is no analytic methodology (discipline) for composites comparable to linear elastic fracture mechanics for metals,

(e) a *lack of verified methodologies*, based on the physics of filamentary composite structural behavior; composite designers are not able at this time to design with the same degree of confidence for, longevity, damage tolerance, durability, and other aspects of structural integrity including fracture as they can with metals; as

an example, fracture toughness, a rigorously defined and measurable characteristic of metals, is not well defined nor is there an agreed-upon, measurable characteristic for advanced organic composites,

- (f) *high production costs* requiring improved manufacturing technology,
- (g) *the adverse effects of lightning strikes on structural integrity*, and
- (h) *the potential for smoke and toxicity from fires*.

11. *Technology Application*—The technology in this study, while restricted to advanced organic composites in support of the subsonic national aeronautics goal, will support the other national aeronautical goals, the supersonic cruiser, and the trans atmospheric vehicle. One example, the organic composite methodologies to assess fracture, longevity, damage tolerance, and durability will provide the foundation for the methodologies to address the additional complexities of the high temperatures of high supersonic and hypersonic flight. These methodologies would be generally applicable to matrix materials other than organics and may offer attractive potential for high-temperature structures, i.e., metal matrix and carbon-carbon.

12. *Large-Scale Tests*—Large-scale tests of composite structures are considered essential to the full development of composite technology. Such tests provide important information related to design, tooling, manufacturing, and testing. However, for a given program of necessity the data are restricted to selected materials and a selected structural design and do not extrapolate easily to the broad range of composite materials and structural configurations available to designers. Thus, to be effective, technology development programs need to address composite built-up structural elements as well as components.

The committee believes that the technical issues identified above can be resolved through appropriate R&T. Cost is an issue but it is not separable from the technical issues. The committee believes affordable aircraft will be forthcoming if its recommendations for R&T are implemented. A major potential barrier is an attitude in government circles that government support is no longer necessary or justifiable. The committee does not agree with this position.

The committee concludes that the government must consider the development of a new advanced organic composite R&T structures program for aircraft.

Recommendations

Based upon its findings the committee offers the following recommendations noting that the tough budget decisions made a few years ago have created a program malaise and have seriously degraded the leadership role of NASA in the important technology of advanced organic composites for aircraft structures. Momentum generated by past NASA programs, such as those directed at medium primary structures, is rapidly dissipating. The committee believes it is timely and appropriate to begin a BOLD NEW PROGRAM (BNP) characterized by the following *THRUSTS*, which are discussed in more detail in Sections I and II of the report Supplement. The reader is encouraged to examine the Supplement.*

THRUSTS

1. *NEW STRUCTURAL CONCEPTS*: The BNP should foster full recognition that the basic components of advanced organic composites are filaments and matrix, i.e., "strings" and "glue." A new way of thinking needs to be promulgated to overcome 40 years of devotion to design concepts that may be appropriate only for isotropic metallic materials. It has been said with much accuracy that many, if not most, of the present composite applications are "black aluminum"; the metal material in a metal design has merely been replaced with black filamentary composite material. More innovative design and manufacturing concepts that fully utilize the inherent characteristics of composites must be pursued. University programs could be helpful here. (Pages 23, 24, 26, 29)

2. *MANUFACTURING*: The BNP should encourage new manufacturing methods that will exploit the filament and matrix nature of composite materials

*Some of the committee's views relevant to these *THRUSTS* and the following *RECOMMENDATIONS* are on the pages of the Supplement noted after each summary statement.

and reduce production costs. Structural concepts should be integrated with manufacturing. There is a tremendous investment in metal shaping and fabricating tools, but progress in the application of advanced composites has been and will continue to be impeded if the tooling for metals continues to be used for filamentary composites. "Free" thinking, leading to new and improved concepts, will be discouraged if the designer thinks in such terms as five-axis milling machines, drill presses, and conventional tooling concepts. (Pages 25, 26, 29)

3. *CRITICAL EXPERIMENTS*: Experiments (of sufficient scale) are the linchpins to a better and sufficient understanding of the fundamental issues of fracture, longevity, damage tolerance, durability, and other issues of structural strength and integrity. Critical work should be identified and supported. (Pages 26, 29)

4. *DESIGN METHODOLOGY*: The development of analytical methods that blend theory and empirical and experimental data, and permit extrapolation of data from the laboratory to full-scale design, is very important. Analytical methods for failure analyses are needed for designers to assess properly the structural margins of safety. It is important to recognize that large finite-element programs that make use of supercomputers will spew out reams of useless answers if the failure theories and analytical methods are in error. The design methodology is only as good as the experimental data base upon which it is structured and hence this analytical thrust must be closely coordinated with and depend on experiments for proof. (Pages 24, 25, 26, 29)

5. *DATA BASES*: The term "data bases" as used herein relates to material and structural matters required to reduce the risks of new composite structure designs to levels acceptable to designers and chief engineers. Data pertinent to such matters as material properties (ranging from tensile ultimate strength to behavior at moderate and high temperatures to moisture absorption), methods of testing, compressive behavior of laminates, and bonded-joint design have to be addressed. Well-organized and well-documented data bases should be published and disseminated to appropriate government, industry, and academic organizations. It is recognized that the development of material data bases will be a more difficult, drawn-out process than that for other technical matters due to the dynamics of material development. This difficult matter should be explored with industry to identify what should be pursued. (Pages 23, 26, 29, 36)

6. *EDUCATION*: Generations of young engineers are needed whose baseline knowledge is orthotropic rather than isotropic, heterogeneous rather than homogeneous, and who deep down in their psyches regard metals as a special case of filamentary composites. The BNP should address resources to the engineering schools to help achieve these goals. (Pages 25, 26, 29)

RECOMMENDATIONS

Based on the preceding observations and committee deliberations, and Sections I and II of the report Supplement, the committee *RECOMMENDS* the following:

1. The government, through NASA, DOD, and FAA, should establish a BOLD NEW PROGRAM for advanced organic composites research and technology development (R&T). The committee believes an order-of-magnitude increase in funding is justifiable on the basis of the expected returns. (Pages 36, 37)
2. The objectives of the BOLD NEW PROGRAM should be to enlarge the technology data base and to enhance the opportunities for early application of the technology. (Pages 23, 29, 38)
3. The BOLD NEW PROGRAM should be innovative and visionary, and the R&T effort should provide the government and industry with the capability to capitalize on the potential of advanced organic composite materials. (Pages 23, 25, 40)
4. The BOLD NEW PROGRAM, in addition to basic R&T, should be directed at cost reduction from material to design through construction and testing; the program should expand the related data bases, include necessary large-scale technology validation activity, and appropriately support related academic activity. (Pages 23, 37)
5. NASA, DOD, and FAA should jointly define and implement the program with inputs from industry and the universities and consider joint ventures for large-scale expensive projects. (Pages 25, 26, 29, 31, 34, 36, 37, 41)

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Supplement:
Summary of Committee Study

Section I

Program Assessment

In its review of advanced organic composite technology the committee considered (a) their potential advantages, (b) inhibiting factors or barriers to their application, (c) technical issues that need to be resolved to help accelerate their application, and (d) possible actions the government could take (through the National Aeronautics and Space Administration [NASA], U.S. Department of Defense [DOD], and Federal Aviation Administration [FAA]).

The committee's views on these matters are summarized in this Supplement (which addresses aircraft manufacturers and airlines, composite material manufacturers, and government agencies) based on the committee's review of the material presented to it and its own deliberations.

AIRCRAFT APPLICATIONS

The committee used four classes of aircraft—large transports (and airlines as users), rotorcraft, high-performance aircraft, and general aviation—for its assessments of potential advantages, inhibiting factors, technology needs, and possible government actions. Following is a summary of these assessments.

Potential Advantages

Advanced organic composites can, if the technology is fully developed, provide appreciable advantages for all classes of new, advanced aircraft. Some of the more important advantages are listed in Table S-I-1. These range from reduced costs for design, manufacturing, and operation of the aircraft to aerodynamic and structural tailoring to improved crashworthiness and life. The importance of each varies with class of aircraft.

The subjects of reduced structural weight, increased aircraft productivity, and reduced costs are fundamental drivers of research and technology for all classes of

TABLE S-I-1 Potential Advantages

Subject	Assessment			
	Large Transports & Airlines	Rotorcraft	High- Performance Aircraft	General Aviation
Reduced structural weight	1	1	1	1
Increased aircraft produc- tivity	1	1	1	1
Reduced costs: design, de- velopment, manufacturing, and operations	1	1	1	1
Aerodynamic and structural tailoring	2	1	1	2
Increased stiffness and reduced fatigue	2	1	1	2
Improved performance	2	1	1	2
Reduced corrosion, main- tenance, and repair	2	1	1	2
Improved crashworthiness	2	1	2	2
Damage reduction	2	2	2	2
Long life	2	2	2	2

KEY: 1--Very important
 2--Important
 3--Significant

aircraft. With advanced organic composites, primary structural weight reductions of 20 to 25 percent are probable and up to 50 percent potentially possible, compared to a metal structure. This can be translated into various combinations of longer range, reduced fuel consumption, or larger payloads.

Reductions in cost for design, development, and manufacturing will help broaden the market for individual aircraft and improve their competitive position. Reduced operational and life-cycle costs are possible because of the potential for reduced initial and operational costs through the integration of design and manufacturing, the manufacture and assembly of fewer parts, the automation of manufacturing, the reduction of labor requirements, and the increase in productivity per unit of cost.

Composites produce smooth, finished surfaces and permit variable contours to maximize aerodynamic efficiency. They can be designed precisely to net-shape with fiber orientation to give the desired stiffness and achieve maximum structural efficiency. Structural efficiency is enhanced further by the reduced susceptibility to

fatigue of composite structures. These factors combine to improve aircraft performance, and they synergistically interact with other factors that increase operational efficiency and, thus, productivity.

The matters of tailoring stiffness, reducing fatigue, and lowering structural weight are relatively more important for rotorcraft because of their severe operating environment and higher weight empty fraction.

Because composites are stiffer than metals, do not corrode, and experience less fatigue, they should require less repair and maintenance than metal structures. This basic stiffness advantage is important to all of the aircraft classes. For rotorcraft, additional potential advantages are reduced vibration and cyclic loads. For high-performance aircraft a significant potential advantage is greater capability to sustain repeated high-stress maneuvering.

Although a conventional composite structure has relatively poor crashworthiness due to its lack of inherent plasticity and residual strength following yield, current Army and FAA research indicates that, when properly designed to enhance crashworthiness, a composite structure can have a higher specific energy absorption than a metal structure. This represents a fertile area for additional research if the full benefit of composite structures is to be realized. The potential for improved crashworthiness, at a reduced weight penalty, is important for both civil and military rotorcraft.

Inhibiting Factors

Use of advanced organic composites has been limited because of the inhibiting factors listed in Table S-I-2. Thus, the potential advantages addressed above have not been fully exercised.

Among the major inhibiting factors for all aircraft classes are the high costs of design, development (including certification), and production of advanced organic composite structures. Design and development costs are pervasive. They involve such matters as (a) the lack of technology data bases from design to test to certification to manufacturing, (b) limited understanding of failure mechanisms and related analytical methods for predicting and designing to avoid failure, (c) the inability to certificate (acceptance for military aircraft) with assurance, (d) low tolerance to accidental, natural, and battle damage, (e) the need for nondestructive inspection and testing techniques, (f) difficulty in making repairs in the field, and (g) the low-stress limits of present advanced organic composite materials.

Certification deserves special comment. It is a cost item because of the time and complexity of a process that in the end has not had high success. This has resulted in an understandable reluctance on the part of designers and manufacturers to apply composites aggressively, particularly in civil aircraft. Technical uncertainties associated with design and development, and the certification process itself, are inhibitors. The certification agencies (FAA and DOD) also have difficulties in identifying appropriate tests and processes for validating safety, performance, and life characteristics and in assessing test data. The difficulties experienced by the

TABLE S-I-2 Inhibiting Factors

Subject	Assessment			
	Large Transports & Airlines	Rotorcraft	High- Performance Aircraft	General Aviation
High costs--design, de- velopment, and production	1	1	1	1
Lack of technological data base	1	1	1	1
Understanding failure mechanisms	1	1	1	1
Low tolerance to damage	1	1	1	1
Inadequate nondestructive testing	1	1	1	1
Certification difficulty	1	1	1	1
Difficulty of damage repair in field	1	1	1	2
Lack of design experience/ education	2	2	2	1
Costly maintenance and repair	2	2	2	2
High acoustic response	2	3	3	2
Limited manufacturing capability	2	2	3	2
Inconsistent manufacturing quality	2	2	2	3
Low-stress limits	2	1	1	3
Brittleness of matrices	3	2	1	3
Adverse effects of environ- ment	3	3	3	3
Material cost	2	3	3	2
Ability to design thick-wall components	3	1	2	3
Erosion of rotor blades	3	1	3	3
Low tolerance for high temperature	3	3	1	3

KEY: 1--Very important
 2--Important
 3--Significant

certification agencies are exacerbated by the lack of standardized definitions and test procedures for composites.

The inability to make a full commitment to composites is in part due to the lack of advanced production techniques, procedures, and automation. The inability to handle design, development, and production factors expeditiously raises costs and reduces product quality and performance. This, in turn, will adversely affect the scope and rate of technology development. Production (i.e., manufacturing) is inhibited by limited capability and capacity, high tooling costs, and inconsistent quality. The ratings for these factors range from important to significant depending on the class of aircraft (Table S-I-2).

Factors such as low-stress limits, brittleness of matrices, and environment (Table S-I-2) affect all aircraft classes and vary in importance with class. The ability to design (and test) thick-walled components is very important to rotorcraft. Such components are used extensively in rotors and major structures, and are expected to find their way into drive trains. Also important in rotorcraft design is avoidance of rotor-blade erosion by sand and dust, rain and hail. A unique concern for high-speed, high-performance aircraft is the low structural tolerance of advanced organic composites to high temperatures.

Costly repair and maintenance and lack of design experience and education are considered universally important inhibitors. For general aviation, experience and education are very important and of special concern because these manufacturers have limited production facilities and staffs, and find it difficult to compete with the large firms for trained personnel.

Comments specifically pertinent to airline operations are contained in Appendix B, special correspondence from the Air Transport Association of America.

Technology Needs

To gain the potential advantages of composites, the inhibiting factors must be reduced or removed. The needs, among a broad spectrum considered most significant, are noted in Table S-I-3. They include reduced costs, concepts and design innovation, and data bases, among other items.

Costs There is no question that costs must be reduced. Much of the costs are associated with manufacturing (tooling, processes, and labor), some with development testing and certification, some with materials (which will become a larger factor with expanded use of composites in a given design), and some with design.

New Concepts and Design Innovation The full benefits of composites will not be realized until designs (and manufacturing processes) take advantage of the unique characteristics of composites and composite structures are not designed and built like metal structures. This requires new design and manufacturing concepts; it requires innovation.

TABLE S-I-3 Needs

Subject	Assessment			
	Large Transports & Airlines	Rotorcraft	High- Performance Aircraft	General Aviation
Reduce costs	1	1	1	1
New concepts and design innovation	1	1	1	1
Technical data bases	1	1	1	1
Failure mode analysis/under- standing	1	1	1	1
Design and manufacturing integration	1	1	1	1
Simplify and accelerate certification/acceptance	1	1	1	1
Education and training	2	2	2	1
Easy repair and field re- pairability	2	2	2	2
Advanced composites program	2	1	3	3
High-temperature, long-life processable systems	3	3	1	3
Honeycomb and sandwich systems	3	3	3	3

KEY: 1--Very important
 2--Important
 3--Significant

Data Bases The large manufacturers are building data bases for design, testing, and certification. These data bases are not universal nor are they available to other manufacturers. The proliferation of new basic materials and composites, and designs and processes make the maintenance of data bases complex and expensive. Some semblance of order and standardization is required if the time, complexity, and cost of design and testing are to be reduced and certification is to be approached with confidence.

Failure Mode Analysis and Understanding If designs are to be sound and certifiable, failure and its progression and an understanding of how to design to avoid failure under severe operating conditions must be predictable. Analytical tools—theoretical and/or empirical—that provide this capability are needed to assist in design and testing for safe, long-life composite structures.

Design and Manufacturing Integration To capitalize fully on composites, innovation

in design must be integrated with innovation in manufacturing. The very processing of composites affects the characteristics of the material and the finished part. The activities are interdependent not independent. Automated manufacturing will reduce production costs and improve quality control.

Simplify and Accelerate Certification There are two parties to certification—industry and government, i.e., the producer and the certifier/acceptor. The producer needs to know what to design for and how to design and test for certification. The certification agent needs to specify requirements and procedures that will satisfy guardianship of the public interest. Data bases on related matters will help. There is a need for a high level of confidence in the ability to certify a new composite aircraft design including the realization of reduced certification process time and cost. Particular attention to simplification and acceleration of the process is needed and warranted.

Education and Training Most people involved in composites today were not trained in this specialty field. Expanded development and application of composites will require an enlargement of the cadre of professionals and technicians in the field. The problem is specialized training in this relatively new field. Needed is cooperative effort among industry, government, and universities on both near- and long-term educational matters.

Advanced Composites Program An advanced composite rotorcraft program that addresses generic technology development (noted in the discussion on inhibiting factors pertinent to rotorcraft) would significantly improve these aircraft. The technology development effort must include validation of the generic technology at reasonable system scales and give attention to new, innovative rotorcraft concepts. Related work for transport and the other classes of aircraft, with a focus on generic primary structures (fuselages and wings), is considered by the committee to be an important, integral part of the technology development effort for helping U.S. aircraft manufacturers maintain a competitive edge in world markets.

Ease of Repair and Field Repairability Important to all aircraft classes is ease of repair at the maintenance base and in the field from time, cost, and tooling considerations. Owners and operators need techniques and tools that allow simple and inexpensive repairs in the field. This is especially important for military and airline operations. Service disruption results in loss of mission or revenue.

High-Temperature, Long-Life Systems Composite systems that can tolerate high temperatures, have long life, and are readily processed into components and structural elements are critical to the development of future high-speed and high-performance military aircraft. These aircraft will operate at high-supersonic (in the future possibly at hypersonic) speeds for extended periods of time. Organic composite materials and structural designs are needed that can withstand temperatures to about

550°F. But, of course, much higher temperatures must also be dealt with for exterior structures and propulsion system elements.

Honeycomb and Sandwich Systems Although there has been a movement away from honeycomb and sandwich composite structures due to poor past performance under conditions of high humidity and widely varying temperatures, they warrant re-examination because these systems are efficient and relatively inexpensive. Honeycomb and sandwich systems can be very important to general aviation and have significant value for the other aircraft classes.

Possible Government Action

Table S-I-4 lists some of the more important actions that government agencies could take, related to aircraft design, manufacturing, and testing, to help further the application of advanced organic composites. The government agencies can: (a) build technology confidence, (b) continue support of basic research, (c) support, selectively, the development of data bases, (d) support development of new structural concepts and innovative structural designs including manufacturing processes, and where appropriate, large-scale (including flight) integrated system concept testing for technology development, (e) develop fatigue and failure mechanism analyses, (f) identify and pursue activity to reduce the time, cost, and uncertainties of certification of composite aircraft structures, (g) support development of advanced manufacturing techniques and processes, and (h) support fellowships and other educational endeavors to help improve the cadre of professional and support people in the field of composite aircraft structure design, development, manufacture, testing, and operation.

Other subjects warranting government support, because they are important or of significant value, involve the exploration of the potential for application of new and innovative composite structures, the development of technology pertinent to damage-tolerant design, and the definition and development of an advanced composite aircraft technology program encompassing large-scale validation of analyses and small-scale experiments.

MATERIAL MANUFACTURERS

Table S-I-5 summarizes the observations of the committee with regard to three classes of materials having special interest to aircraft designers and manufacturers: (1) epoxy resin pre-impregnated fiber (prepreg), (2) bismaleimides/polyimides (BMI/PI) for higher-temperature applications, and (3) thermoplastics for manufacturing advantages.

Potential Advantages

Epoxy resin prepreg has the advantages of lower-cost manufacturing, existing

TABLE S-I-4 Possible Government Action

Subject	Assessment			
	Large Transports & Airlines	Rotorcraft	High- Performance Aircraft	General Aviation
Build technical confidence	1	1	1	1
Support technical data-base development	1	1	1	1
Support basic research	1	1	1	1
Support new concept and in- novation design and man- ufacturing	1	1	1	1
Develop fatigue and fail- ure mechanism analyses	1	1	1	1
Reduce time and cost--cer- tification/acceptance	1	1	1	1
Support fellowships	1	1	1	1
Explore potential appli- cations	1	2	2	2
Develop advanced composite (flight) aircraft technology program	2	2	2	3
Address manufacturing cost reduction	2	2	2	2
Develop technology for thermoplastics manufac- ture	2	2	1	3
Develop damage tolerant design technology	3	1	3	3

KEY: 1--Very important
 2--Important
 3--Significant

data bases (within a few companies), experience, and available facilities. However, there is significant room for technical advancement in each area.

BMI/PI composites can withstand the moderately high temperatures (up to about 550°F) associated with moderate supersonic flight speeds. Like epoxy, to some degree, the kinds of tools needed for manufacturing are in-hand, but data bases and experience are less and costs are higher than for epoxy.

Thermoplastics have high potential. They can handle higher temperatures than the other organic composites noted and possess higher toughness. There is also a potential for lower-cost, uniform manufacturing.

TABLE S-I-5 Summary Observations--Materials

Potential Advantages	Inhibiting Factors	Needs	Possible Government Actions
<u>Epoxy</u>			
Lower costs	Moisture damage	Raise toughness	Develop
Existing data base	Low toughness	and temperature	measurement
Experience	and ease of damage		and evaluation
Existing facilities	Supportability		techniques and processes
<u>Bismaleimides/polyimides</u>			
High temperature	High cost	Improve processing	Develop measurement and evaluation techniques and processes
<u>Thermoplastics</u>			
Greater reproducibility	High cost	Improve manufacturing methods	Develop measurement and evaluation techniques and processes
Ease of repair	Availability		
Higher temperature	Need for high temperature and pressure for processing	Increase data base	
Higher toughness			

Inhibiting Factors

Epoxy systems are subject to strength reduction, i.e., environmental damage, due to moisture ingestion if detailed attention is not given to design. The materials have low toughness and are relatively easily damaged. This can lead to problems concerning damage detection, knowledge of the extent of damage and failure potential, and when and how to repair.

BMI/PI materials are relatively expensive. They are inherently brittle and possess low toughness. These factors lead to the same class of supportability issues that epoxies have.

Thermoplastics have had relatively little application in aircraft. Their costs are high, they are relatively unavailable, and they require high pressure and temperature for forming components.

Needs

Epoxy's major drivers, from material considerations, are increased toughness and higher usable temperatures than are available today. However, considerable progress in toughness has been achieved since 1985.

For BMI/PI, one of the more important needs is to improve the ability to process these materials with consistency and low cost.

Possible Government Action

In the area of materials the committee believes that the government can be of most help through attention to the development of standards of measurement, evaluation techniques, and basic material production processes. Although industry can develop materials, it is not in the best, most unbiased, position to develop and set standards for the measurement and evaluation of materials. It is the view of the committee that the detailed development of new materials, manufacturing processes, and applications can be left essentially to the materials industry in concert with the aircraft designers and manufacturers. However, in the area of basic understanding of chemical and mechanical processes, government research and technology development support would be very useful in accelerating fundamental understanding, leading to industrial development and application.

GOVERNMENT AGENCIES

The views of government representatives on important technology development needs are summarized in Table S-I-6. The technology development needs noted for the Army relate to rotorcraft; the Navy and Air Force needs relate principally to high-performance aircraft; the FAA to transport, general aviation, and rotary-wing aircraft; and NASA to generic research and technology. Observations common to all aircraft classes are summarized in Table S-I-7.

The data in Tables S-I-6 and S-I-7 reinforce the earlier industry discussions of needs, potential advantages, inhibiting factors, and needs.

Potential Advantages

The government agencies see common advantages and benefits associated with advancing the state of technology of advanced organic composites. These benefits relate to broader design, operational, and mission flexibility and thus greater performance and/or productivity. They see the potential for reducing the costs of composite structures through enhanced technology, advanced designs, and greater application of composites. The committee agrees with the government agency representatives' belief that successful pursuit of these advantages will help maintain U.S. competitiveness and preserve U.S. jobs in aircraft development and production programs. Thermoplastics have interesting potentials but there is relatively little experience with applications. Application would be enhanced with improved

TABLE S-I-6 Individual Government Agency Views on Advanced Organic Composite Technology Development Needs

U.S. Army

Composites for rotor blades that withstand rain and sand
 Design criteria and standards for damage, durability, and fatigue
 Design for damage tolerance, durability, and crashworthiness
 Methods (standards) for handling fatigue in a uniform and consistent manner
 Realistic qualification procedures

U.S. Navy

New materials and material forms to meet more severe design conditions, i.e., woven composites and new resin systems
 Systems for better impact and damage resistance, survivability, low cost, supportability, crashworthiness, fatigue life, durability, and maintainability including analytical tools
 Postbuckling analysis methodology
 Certification procedure definition
 Low-weight design
 Issue areas: airframes and structural integrity, landing gears, load and life management, supportability, and electromagnetic compatibility

U.S. Air Force

Research and development: thermosets--new polymer concepts and resin characterization, processing science, ordered polymer fiber and film, molecular composites, opto-electronic materials
 Supportability: field repair materials, postfailure analysis, paint removal, and thermoplastic support
 Manufacturing technology and science: regarding computer-aided cure of complex shapes, integrated composites center, large composite aircraft
 Thermoplastic and organic materials for propulsion systems

Federal Aviation Administration

Detection of understrength bonds (all classes)
 Failure analysis methodology
 Standards for material property testing
 Cost-effective finite element analysis techniques for complex-load transfer areas
 Flammability, toxicity, and smoke characteristics of materials
 Damage growth analysis
 Repeated-load response
 Statistical analyses to allow reduction of mechanical testing
 Full-scale component response versus coupon response and data scatter
 Crashworthiness
 Lightning-strike behavior

National Aeronautics and Space Administration

Systems characterization: mechanical properties, damage tolerance, micromechanics/failure, and environmental effects
 Structural concepts, efficiency, and tailoring
 Gradients, discontinuities, cutouts, and damage
 Postbuckling and nonlinear effects and analyses
 Local and global structural analyses including failure mechanisms and analyses
 Subscale wing-box and fuselage-shell modeling
 Filament-wound structures
 Thermoplastics

TABLE S-I-7 Summary of Government Agency Views on Advanced Organic Composite Technology Development Factors

Potential Advantages	Inhibiting Factors	Needs and Possible Government Action
Reduced structural weight and increased stiffness	Costs; design, development, manufacture, certification, and maintenance and repair	Cost reduction; design, manufacture, test, and certification
Aerostructural tailoring	Data base for design and test	Data bases for design and test
Design flexibility	Manufacturing techniques and capability	Design and manufacture innovation
Increased aircraft performance and/or productivity	Limited experience and trained personnel	New concepts for structural design and manufacture
Fatigue resistance	Impact damage susceptibility, i.e., low damage tolerance and understanding failure mechanisms	Design and manufacture integration
No corrosion	Nondestructive and non-invasive test and inspection methods	Certification; simplify and accelerate
Longer life	Ability to certificate	Build technology confidence
Reduced part count and manufacturing costs		Large-scale systems; advanced composites airframe program
Reduced life-cycle costs		Thermoplastics; increase attention
Competitive edge and jobs		Education; professional and technical support

manufacturing technology and enlargement of design and development data bases. Particular attention needs to be given to the development of low-cost manufacturing processes.

Inhibiting Factors

Government agency representatives view inhibiting factors as relating to high costs; limited design, development, and testing data bases; integration of design and manufacturing; certification; and the lack of appropriately trained engineering personnel and technicians. These are the same factors considered important by the designers and manufacturers, and by the committee.

Needs and Possible Government Action

It is the view of the committee that the government can play a significant role in gaining the advanced organic composite benefits that have been identified in this study through the reduction or elimination, selectively, of inhibiting factors.

The government could help reduce costs by supporting technology developments that improve design, manufacturing, testing, certification, and maintenance processes; including support of related definition, development, and sustenance of data bases. Other key factors in cost reduction and leadership are new concepts and innovation; pertinent is work related to structural design, manufacturing, certification, and maintenance processes.

Certification is difficult under normal circumstances, and with composite designs even more so. The government could review the entire certification process, including assessment of technology development needs, and pursue adjustments to the process that can result in less time-consuming, less costly certification of composite structures.

In all of this work it is important to build confidence in the technology and processes for handling composites from design to certification. This will require detailed attention to technology development including large-scale work to validate small-scale experimental data and analyses.

Thermosets have received the most attention in past programs. Thermoplastics, on the other hand, have interesting attributes, such as reproducibility, manufacturing simplicity, and high toughness and temperature capability, which may well outweigh their higher manufacturing costs. These materials should be included in the program.

Education programs supported by special grants should be developed to train engineers (and technicians) in the application and use of composites.

A summary of key technology program considerations for all aircraft classes that should be factored into this planning from a review of government agency considerations is presented in Table S-I-8. The committee did not attempt to identify a top-level technology development program plan. This level of planning should, of course, respond to policy and programmatic objectives set by responsible management. The committee believes that the government's program policy, objectives, and plan should be developed, in concert, within the responsible government agencies (NASA, DOD, and FAA). This will be a complex undertaking. It is recognized that the development of an advanced organic composite material technology program is indeed complex because of the generic as well as the unique considerations associated with aircraft classes and their users.

Regarding materials, the agencies agree that the basic (generic) technology should be pursued. They believe, and the committee concurs, that the government should direct attention to basic R&T and standards for assessing and testing, and that industry should pursue product development. The value of pursuing material technology development includes cost reduction (though not assessed as a major life-cycle, cost-controlling factor), greater reproducibility, ease of repair, and greater

TABLE S-I-8 Government Agency Summary--Technology Program Considerations,
All Aircraft Classes

Technology Development

Effects of discontinuities; cutouts, gradients, and damage
Modeling and full scale; wing boxes and fuselage shells
Airframe structural integrity, landing gears, and electromagnetics
Aerostructural tailoring
Filament-wound structures
Methods for controlling fatigue and standards for design
System response to repeated loads
System characteristics; mechanics, damage tolerance,
failure modes, environmental effects, and energy attenuation
Supportability; maintenance and repair in depot and field
Testing; bond strength, standards, techniques, and instruments
Lightning-strike protection without weight penalties

Components and Systems, Analytical Tools

Complex load transfers; finite element techniques
Local and global systems including failure mechanisms
Postbuckling and nonlinear effects
Failures and damage growth

Materials and Processing

Characterization; flammability, toxicity, and smoke
Improved erosion characteristics
Thermoset research and technology development
Thermoplastic research and technology development
Materials and material forms for severe design conditions
Manufacturing technology; reproducibility, automation, and
effects on products
Data bases
Nondestructive testing

Design Concepts and Innovation

Low cost and weight
Criteria and standards; fatigue, damage, and durability
Damage tolerance and durability
Survivability, crashworthiness, and fatigue life
Structural concepts; efficiency and tailoring
Maintainability and repairability

Certification Capability

Definition of processes and procedures
Full scale versus coupon response and scatter
Statistical analysis to reduce testing and costs
Standardized processes and definitions

toughness (reduced damage susceptibility and failure response). Inhibiting factors today are high material and processing costs, low levels of toughness, high degrees of response-to-damage, rate-of-failure progression, and the inability to operate at high temperatures.

SUMMARY OF KEY OBSERVATIONS

In summary the committee notes the following about the development and application of advanced organic composites:

- **Advantages**—The potentials for weight reduction, increased performance, and/or mission flexibility, ease of manufacturing and assembly, and reduced life-cycle cost.
- **Drivers**—Increased performance, mission flexibility, new capability, and foreign competition.
- **Drawbacks**—If technology development is not pursued, there are high costs, susceptibility to damage, and limited serviceability and supportability.
- **Problems**—Damage tolerance: design capability (analysis, data bases) related to failure mechanisms, bonds, joints, and other elements; repair; nondestructive evaluation; environmental effects; high-temperature capability; low-cost manufacturing; and certification.
- **Unresolvable issues**—No real unresolvable issues, but need management cultural changes, more experience, and facilities.
- **Government role**—Technology development, new concepts (innovation) for design and manufacturing, test and evaluation processes, standards, data-bank development and support, education, and improved certification processes to build confidence in design and application. With regard to materials the committee believes that the government should help develop materials system characteristics, standards, processes, and techniques for measurement and evaluation of materials, and leave focus on materials and material system development to the materials industry.

The committee's key observations are the following:

- Despite successful application of organic composites to aircraft, their full potential is largely unused.
- Foreign competition (with government support) has been more aggressive in applying advanced technology and will continue to be aggressive.
- The driver for composites has been performance. The new emphasis must be on reduced costs—initial, operations, and support. Affordable aircraft is a must for both civil and military systems.
- Innovation and data-base development and documentation are other points for program emphasis.
- New programs must be directed at significant increases in technology: new ways to design, test, build, and maintain low-cost, high-strain, integrated-structure

aircraft. Selective generic component and system test work is required. Funding for such work falls short in all government programs.

- The military does provide substantive support to R&T programs for highly loaded, high-performance aircraft, but this does not relieve the needs noted.
- Future use of composites depends upon the level of confidence that designers, project managers, and corporate management have in the available technology.
- A bold new program will have to be defined and brought to the attention of NASA and other involved government agency managements, the administration, and the Congress. Part of this program development task will be to make clear the inseparable roles of government and industry.
- Program planning needs to involve the government agencies, industry, and the universities. The definition, support, and conduct of critical, large, expensive test programs should also involve these groups, in the form of joint ventures.

Thus, the committee takes the position that the full potential of composites for aircraft are far from realized, and,

(1) the government's program must be directed to the future and be appropriately visionary;

(2) it is incumbent on the government (NASA, DOD, and FAA) to provide the nation, through industry, with the capacity to capitalize on composite material potential; and

(3) a bold new technology development program is needed.

It is the view of the committee that these actions will provide the nation with the technology that will allow the design, development, and certification of cost-effective composite aircraft with high levels of confidence.

Section II

Response to Government Issues and Questions

The role of government in aeronautical technology development, particularly that of the National Aeronautics and Space Administration (NASA), has been brought into question due to budget constraints. This has had an adverse impact on NASA's support for advanced composite structures work, especially related to civil aviation. For example, NASA's fiscal year (FY) 1986 budget for research and technology (R&T) development was under \$4 million. The Federal Aviation Administration's (FAA) budget was also quite low, less than \$1 million for safety/certification-related composite structures R&T.

Because of its constrained budget for advanced organic composite structures, NASA raised a series of questions related to a future NASA R&T program: (1) Can a new program help resolve industry needs? (2) Is a long-term major national effort appropriate? If appropriate, (3) What is the government's role? (4) Where can the government best apply resources? (5) What specific program guidance and priorities are appropriate? and (6) What are the key barriers to the consideration of composites as routine structural material?

FUTURE R&T PROGRAM

New Program

The committee believes that the current R&T program in government is not deep enough or broad enough to provide the data required for sound design and development of advanced organic composite aircraft with reasonable industrial risk. A new R&T program is indicated if, as a matter of national policy, the United States wants to maintain a leadership role and a competitive advantage over other nations in aircraft design, manufacturing, and sales.

Major National Effort

The committee believes that a major national effort is warranted in view of the complexity, high risk, large investment, and high-potential national payoff of an effective, successful R&T program. A mitigating factor in favor of a national, not a private, effort is the little likelihood of industry mounting and sustaining an appropriate program and appropriately disseminating the program data.

Government's Role

In the view of the committee, the government's role is to orchestrate the definition and implementation of an appropriate R&T program with inputs from industry and the universities. It is anticipated that significant elements of the program will be carried out in-house and under contract and that some parts of the program will be joint government, industry, and university activity. This joint activity would be characterized by large, significant effort having a large payoff in next-generation designs.

Application of Government Resources

The application of government resources and the identification of program priorities were not addressed by the committee. The committee believes that program funding and priority judgments need to be made in the context of specific future development program possibilities and agency budgets and priorities, and these judgments can best be made by the agencies themselves with industrial guidance and university participation.

Key Barriers

Barriers to the application of advanced organic composites have been discussed in detail in Section I of this Supplement. In simple summary, the lack of data bases and experience combine to affect adversely the time, cost, and certainty of design, development, and certification of advanced organic composite aircraft and form the key barriers to accelerated use of these composites.

PROGRAMMATIC MATTERS

Costs

Costs are possibly the most significant barrier to more rapid growth of composites. The representative but rough estimate of costs noted in Table S-II-1 are for transport and fighter class aircraft.

Manufacturing dominates structural costs. The committee believes that successful investment in manufacturing-processes R&T could significantly reduce total system cost.

TABLE S-II-1 Representative Costs of Composite Structures for Transport and Fighter Aircraft

Cost Segment	Costs (percent)	
	Transports	Fighters
Manufacture	55-50	70-65
Material	30-35	10-15
Quality assurance and test	15	20

At least three manufacturing techniques hold some promise for cost savings over current techniques. These are filament winding, pultrusion, and three-dimensional weaving or other weaving/braiding techniques. Some technology development has been directed to these areas. However, the committee believes that greater investments are required to determine the merits of these and other possible processes and forms of composite materials to enlarge this important activity.

Structures

A government advanced organic composites program plan should be formulated to provide a new effort in primary structures directed to design and development activity during 1990-2010. This should entail development of systems and manufacturing technologies including innovative structural concepts that exploit advanced composites, particularly for wings and fuselages. An aggressive goal would be for new designs to have a 50 percent primary structure weight savings with a 50 percent savings in cost.

The advanced primary structure design concepts would provide greater stiffness, strength, damage tolerance, and system life. Products of this work would include an understanding of design requirements and constraints. The innovative structural concepts work would include tailoring for best use of materials (i.e., do not follow the practices for metal structures). An integral part of the effort would involve textile technology, including three-dimensional braiding, fiber placement, and curing processes.

This kind of primary structures work will require analyses and design-verification testing using component and system subscale models and selectively large-scale, including full-scale, models. The work would also require the development of analytical tools and models and the building of appropriate structural design and manufacturing data bases. Included should be computer-aided design and manufacturing compatibility. These technology tools will assist in identifying and resolving critical structural issues from design to development to certification and operation.

Advanced manufacturing technology should use intelligent machines and tooling, i.e., robotics with built-in (artificial) intelligence to increase productivity, consistency, and quality. Industry must develop new kinds of factories. The materials that would be employed would include thermoplastics and advanced thermosets. To be most useful to industry, this work must be accompanied by the selective building of appropriate data bases.

To exploit innovative, low-cost manufacturing methods there must be parallel development of analytical tools that predict the structural behavior of components made by the new methods. These analytical tools can form the basis for future design and manufacturing procedures. Government laboratories should, through in-house, contract, and grant activity, help develop these analytical tools; and through cooperative efforts with airframe manufacturers, fabricators, and universities, produce and test representative components to verify analyses.

This effort should focus on the development of cost-effective composite structures through the definition of efficient structural arrangements that can be rapidly produced by automated material placement techniques. The government can accelerate this activity by soliciting and sponsoring research to identify new structural shapes, elements, and components that are amenable to low-cost manufacture.

In preparation for such work it would be desirable to have system analyses that provide trade-off assessments of manufacturing cost against vehicle performance.

Technology

FIGURE S-II-1 conceptually presents the structuring of an integrated technology data base for the design, test, and manufacture of composite aircraft. As noted, the term "material properties" involves such matters as the mechanical, thermal, chemical, and electrical properties of the composite materials under consideration.

Needed is the definition of the standard (generic) tests that characterize the basic properties of the materials. This includes the identification of the test type and methods for the measurement of such factors as tensile and compressive strength, shear fatigue, fracture, and thermal and chemical responses to environmental and loading conditions. This is not a simple matter. It is complicated by, among other things, test conditions and specimen geometry.

To be able to compare types of materials, it will, in all probability, be necessary to test various composite systems (thermosets, thermoplastics, and bismaleimides or polyimides) for the same application.

The structural elements noted in Figure S-II-1 include such matters as joints; three-dimensional forms; curved, bolted, and bonded structures; and cutouts, holes, and notches. Important to the designer is life prediction of elements, components, and systems involving knowledge of such characteristics as damage susceptibility, fatigue, compression, combined loads, buckling, and environment response. The life prediction work must be based on analysis and tests. Related documentation must be developed in a timely manner and in a form useful to designers at large.

The areas of substructure and fabrication include such elements as frames,

trusses, panels, and shells, and such activities as lay up and filament winding. The government should help define representative tests and perform tests on representative substructures and fabrication techniques. It should assist in the development of life-prediction analyses and tests.

These and other data would be used to provide the integrated data bases vital to sound design, manufacture, test certification, and other matters critical to the development of effective composite aircraft. The type of data-base documentation needed has to be developed. Here and for the other parts of the data-base activity an issue is: Who will develop, update, and maintain these data bases?

The objective of technology development for innovative design and manufacture of aircraft structures is to build the data base to allow designers to produce components and secondary and primary structures that could cost one-half or less that of current aircraft structures. All types of aircraft are of concern: for the military—trainers, patrol, surveillance, interceptor, and remote-piloted aircraft; and for civil—general aviation, agricultural, and business aircraft, and transports.

Approaches to achieving this objective include pursuit of new concepts and techniques for material and structural design and fabrication. Materials of future

interest include: thermoplastics, advanced thermosets, chopped fibers, bioadhesives, biomaterials, self-skinning foam, and hybrid systems. Design innovations involve: joints, e.g., Windecker wet tow, resistance welded, bonded; foam-stabilized wings and frameless, stringerless structures, e.g., sandwich skins (supported by various cover-to-cover sine wave, corrugated, or honeycomb structures); modular systems, e.g., multicell wing structures and mission adoptive control surfaces; and design and fabrication procedures for such advanced concepts.

Total factory automation is the direction for the future. Fabrication methods R&T should include filament winding and molding techniques—resin transfer, resin injection, compression (for fuselages), and injection (for wing spars). Innovative materials processing should include nonautoclave cure, hot-forming thermoplastics, welded thermoplastics (e.g., resistance welding and fusion welding), and three-dimensional weaving.

GOVERNMENT PROGRAMS

The committee does not believe that the government's advanced organic composites material and structure program supports the level of activity needed to realize the full potential of these materials. Industry has not and is not expected to support the development and dissemination of the data required to accelerate the application of advanced organic composites by the industry.

The aircraft of interest are both civil and military of all classes. With the exception of very-high-performance (supersonic, hypersonic, and transatmospheric) military aircraft, reductions in structural weight and cost of as much as 50 percent are possible with new or improved mission and performance capabilities. The technology leverage gained will not only provide better, less-expensive aircraft with enhanced or new capability but also provide industry with a competitive edge in world markets.

The committee has noted that a new, bold technology development program is needed. The new program would focus on reduction of design, development, production, and support costs. It would support innovative work in the areas of design, test, and manufacture, and assist in rapid, lower-cost certification of resulting advanced aircraft systems. It would focus attention on new uses of materials as well as integrated design and manufacturing to make best use of the properties of composites and void the conservative practice of designs that duplicate metal structures. The new program would address the problem of building data bases and the problems of selective collection, documentation, and dissemination of data to assist design, test, and certification work.

Current programs do not address the spectrum of work envisioned in this bold new program. Funding has been and is expected to continue to be a problem. It is suggested that the concept of joint government, agency-to-agency, and industry-to-government (including universities) programs be undertaken, especially for large-scale experimental work, to help mitigate cost problems.

The institutional means appear to be in place to address the matters of program definition, approval, implementation, and management including reporting and data

dissemination. It is the committee's view that it would be appropriate for NASA to take the initiative in the development of the bold new program with strong participation from the U.S. Department of Defense and FAA, and with the active involvement of industry and universities.

Appendix A

Synopsis of Presentations to the Committee

Three separate sets of presentations were made to the committee. The first set took place at a meeting held on December 17-18, 1985 to review government application and operational experience and research and development activity with advanced organic composite materials. The second set, February 10-11, 1986, was a forum for aircraft manufacturers, an airline operator, and material manufacturers to review their individual experiences, problems, and technology needs. The third set, March 26, 1986, consisted of presentations by government representatives of their views of technology development needs and plans.

The synopsis that follows contains the general sense of the individual presentations in the order they were given to provide an overview of the substantive matters addressed. The views expressed were those of the individual presenters and do not necessarily represent those of the presenter's organization.

COMMITTEE MEETING OF DECEMBER 17-18, 1985

Application and Operating Experience

U.S. Air Force (T. Reinhart)

The Air Force has had 8 to 10 years of operational experience with composites, with good success; composites are being used on rotor blades and other parts of helicopters and for secondary structures on other types of aircraft. Plans indicate that some 40 to 60 percent of the structural weight of new aircraft will be composites.

Operational problems include cracking and corrosion of metal honeycomb, incidents of maintenance damage, quality control in manufacture, paint removal, and repair.

The operational environment appears to have had no adverse effects on composite material and structural characteristics other than corrosion of associated metal parts because of inappropriate composite structure design.

In summary, operational experience is good while maintenance experience is poor. Needs include improved damage tolerance, large-area inspection capability, understanding of failure mechanisms, reliable joints and attachments, and designs that can efficiently handle the transfer of large loads.

For transport class aircraft, there is a need for more design data for highly loaded parts.

U.S. Navy (D. Mulville)

The Navy has had extensive experience with both fixed- and rotary-wing aircraft composite applications. The Navy is favorably impressed with its application of composites including the use of composite load-carrying wing skins and engine casings (replacing titanium).

Problems found are related to operations, maintenance, and repair of battle damage. Care needs to be taken in design where high temperatures can impinge on composite structures (e.g., hot duct blowouts).

The AV8-B aircraft primary structure is about 26 percent composites by weight. The J VX/V-22 structure is expected to be 70 percent composites by weight. An A-6 composite wing-box program is under development, as are studies of composite control surfaces.

Field repairs of composite structures are a major concern. A substantial program is in progress with emphasis on the minimization or elimination of the need for special repair equipment.

Generally there has been little use of thermoplastics, except for repair.

Problems are related to damage during maintenance, erosion/abrasion, and wear around holes. Moisture intrusion and its impact on metal components is a long-term problem. Fuel leakage and lightning strikes are other areas requiring special attention in design and manufacture.

In summary, experience with composites has been good. Operational support and repairs is an area requiring and getting attention in the Navy program.

U.S. Army (P. Haselbauer)

The major composites experience has been with rotorcraft rotor blades (AH-15, CH-47D, UH-60A, and OH-58D) and some secondary airframe components. The OH-58D production articles will have composite main rotor yokes. This yoke has been through qualification testing. The service is moving toward greater use of composites in its future rotorcraft.

The types of problems encountered include: rough skins, skin/core voids, fit tolerances, moisture retention, retention of blade-tip weights, and the sealing of fuel in composite structures. Correction of these design and operating problems requires

detailed attention to design, manufacturing processes including quality control, and knowledge of the operating environment.

In summary, the Army has found that composites are viable for its aircraft structures; trade studies that consider costs, weight, performance, and support dictate the use of composites; three-dimensional stress analyses are important for design; and the use of composite structures for the containment of fuel should be avoided.

Application and Flight Experience

National Aeronautics and Space Administration (L. Vosteen)

The National Aeronautics and Space Administration (NASA) supported an extensive flight-service evaluation program for noncritical advanced organic composite components on a variety of aircraft (L-1011, B-737, CH-54B, 206-L, DC-10, and C-130). Some of these aircraft are still in operation. NASA has also supported component development and transport aircraft flight service on secondary components as part of its Aircraft Energy Efficiency program. An extension of this latter effort included medium-sized primary components (horizontal and vehicle stabilizers). Some of these components are in flight service and others are still to be certified.

In its composite technology program, NASA has addressed environmental exposure, durability and damage, fuel containment, critical joint technology, design for minimum stress, and impact and damage tolerance. The program also included the effects of service time on the strength and other characteristics of composite components.

Ground testing supported the flight program. Unexpected failures did occur in the ground test work. The failures were associated with fastener fits, interlaminar stress, and stress concentration. In general, it was found that secondary stress (not important in metal structures) is important in composites. One concern is that secondary stress may not, and often does not, show up in specimen and small component tests where full-scale loadings and constraints are not and cannot be simulated.

Studies of manufacturing costs show that composites, in quantity, may be less costly than metal structures. They have fewer parts and fasteners and often require less labor, but production automation will be a key factor in gaining competitive costs.

The NASA research and technology (R&T) program includes work on damage tolerance, lightning protection, heavily loaded wing joints, and design concepts for increased stress tolerance and reduced acoustic response.

In summary, in-flight component durability, weight savings, and design and analysis methodology have been successfully demonstrated, and damage tolerant concepts for panels (of wings and fuselages) have been defined. Major needs are seen to be reductions in manufacturing costs, improved damage tolerance, low-cost repair techniques, designs that minimize out-of-plane loads and stress concentrations,

understanding of acoustic transmission and fatigue, understanding of the impact dynamics of structures, and full-scale verification of large system (wing and fuselage) design technology.

Certification and Operational Experience

Federal Aviation Administration (J. Soderquist)

A number of carbon-epoxy structural applications are currently being evaluated by the Federal Aviation Administration (FAA) and a number have been approved for use on transport, general aviation, and rotary-wing aircraft that have been manufactured both in the United States and in Europe. Included in the applications currently undergoing FAA type certification are several all-composite general aviation aircraft.

The earliest carbon-epoxy applications certificated were the B-737 (1973) spoilers and an engine nose cowl outer barrel on the DC-9 (1976).

A structural certification program typically includes material property development, static strength and damage tolerance substantiation, impact dynamic evaluations, and lightning strike evaluations.

A number of issues have been identified that require further research and development (R&D) effort. One example is that of mechanical property test methods in the material property development portion of a certification program. There are currently more than 10 in-plane shear test methods utilized to one extent or another—all yielding different results.

Work is also needed in the following areas: statistical procedures to reduce the amount of material property testing of environmentally conditioned specimens, an analysis methodology capable of predicting material and structural response due to environmental considerations for use in ultimate load static strength assessments, failure criterion, and design criteria for structural fasteners.

The structural integrity of bonded structure is an area of concern. A number of structural bonds have failed in-service and during certification testing. There are no nondestructive inspection techniques available to detect understrength bonds. The degree and level of testing adversely impact costs. A composite material failure analysis capability must be developed.

Current FAA R&D activities include: sensitivity of fuselage structure to fragment impact, repeated-load evaluation methodology, an engineering textbook, and an inspector's handbook. Work is proposed that would (1) develop a nondestructive inspection technique capable of screening out understrength bonds, and (2) develop a failure analysis capability.

In general the operational experience with composites in civil aircraft has been excellent. This is attributed, in part, to the use of 350°F cure material systems, reduced design strain levels, and bolted structures.

A standing list of R&D topics include:

- Effects of load truncation and load sequencing on the repeated-load response of aircraft structures;
- Pressurized fuselage damage containment concepts;
- Statistical variability associated with the initiation of detectable damage and damage growth;
- Nondestructive test methods capable of detecting understrength bonds;
- A primary adhesively bonded structure (PABST) program aimed at developing the technology to design and fabricate repeatable and reliable metal-to-composite and composite-to-composite bonds;
- Material systems having: laminate $G_{Ic} = 5 \text{ in-lb/in}^2$, fiber strain of 2 percent, and laminate transverse strain of 0.6 percent;
- Determination of fuselage and seat structure response to crash loads;
- Flammability/toxicity/smoke characteristics of composites;
- Failure analysis methodology; and
- Mechanical property test methods.

Research and Technology Programs

National Aeronautics and Space Administration (S. Venneri)

The NASA organic filamentary composite program is being reassessed; it is in the planning stage and open to (committee) comment. The objectives for thermosets and thermoplastics are: developing new material concepts and understanding of behavior, including failure mechanics; enabling innovative structural designs and applications; and assisting the achievement of "full" weight and cost savings, and performance gains in future aircraft. The structural weight savings are estimated to be in the range of 25 to 35 percent.

The technology cannot be developed without work on complex structures. However, NASA's large structures (systems technology) programs have been dropped because of budget constraints. These programs were related to large transport wing (C-130 wing box and high aspect ratio [12] dual spar wing) and fuselage technology. In the latter case, some small-size panel work continues.

The budget cut in fiscal year (FY) 1985 for systems R&T was \$25 million. The R&T base program remained in the \$4 million to \$5 million range. These budgets cover contracted R&T, not in-house staff and support. The plan is to add more funds in FY 1986 to the R&T base program. However, the budget level is such that large-scale R&T work will not be supportable.

Some detailed wing R&T is planned relating to durability and damage, fuel containment, lightning damage avoidance, and critical joints. Fuselage work planned includes: damage tolerance, pressure containment after buckling, cutout and joint design, impact dynamics, and acoustic transmission and characteristics.

The NASA program is to be a combination of in-house and industry activity that will include material concepts, structural concepts, and fabrication techniques. Industry will be most active in this latter area. Related technology work to be

pursued will cover aerodynamics, acoustics, active controls, and interdisciplinary design and systems integration. The planned program on structural concepts will focus on tailoring for concentrated loads and aeroelastic behavior.

The new materials work will address tough matrix resins, new material forms, and fabrication technology where costs are an important factor that must be addressed with industry participation. The concept verification work planned, though anticipated to be very limited, will involve definition of concepts in some detail, research models, and large element panel/attachment combinations. The modeling work is to include three-dimensional analyses.

In gross the plans for the advanced organic composite program (FY 1986 to FY 1990) are expected to contribute, in some degree, to verified, cost-effective advanced composite, primary structural concepts for wings and fuselages, and address material forms, high-performance polymers, characterization of advanced systems, composites-processing science, and structural element and structural component fabrication.

The NASA program will also encompass metal matrix composites for airframe and propulsion systems through the use of a small business, innovative research proposal activity. This will not be a large effort since the U.S. Department of Defense (DOD) has a significant metal matrix composite program under way. The major thrust of this program will be directed to fundamentals as they relate to fiber-reinforced superalloys for propulsion systems, light alloys for aeronautic (and space) structures, and selected hardware-oriented efforts (mostly for space structures).

NASA is planning a significant move into thermoplastics. The program will hold proper balance between thermosets and thermoplastics. In summary, the future direction of the NASA program will emphasize: the development of anisotropic advantages of composites for advanced structural designs (30-40 percent); fundamental understanding of materials (30 percent); innovative use of new materials (including low cost); and structural analysis and design technology.

U.S. Air Force (D. Roselius)

The U.S. Air Force composites technology program for the 250°F range has been essentially completed. Work on composites useful in the 275°F-450°F range is moving from the DOD 6.2 (R&D) category to the 6.3 (applied) category. Work on 450°F-700°F composite systems is starting with emphasis in the 6.2 category and some work in 6.3.

This R&D program gives credence to the projection that future Air Force aircraft, by weight, will be composed of 50 to 60 percent composites.

The major concerns in the composites arena relate to the understanding of damage and failure mechanics. Composites do not behave like metals. New design approaches are required for composites. Thus, there is a need to develop unique specifications for composites (similar to 83444 for metals). Requirement documents on durability, certification methodology, and damage tolerance are being drafted.

The Air Force has and is supporting large-scale (wing, fuselage, and component)

composite systems R&T development. Manufacturing technology is included in this activity.

Some key design issues requiring technology development are: bolted-joint analyses for strength and life, high stress and strain design, analyses and test techniques, design optimization, ballistic and laser impact, and survivability and supportability damage tolerance and maintenance.

High priority is attached to bismaleimides for high-temperature applications. Some of the major issues are reproducibility and toughness.

Special attention is being given to thermoplastics because of projected advantages such as low manufacturing costs (no cold storage or autoclave cure required, possible to automate, and postforming capability) and good engineering properties (resists impact damage, high elongation/increased allowables, low moisture absorption, damage is visible, slow crack growth, and potential for reduced fire/smoke hazard).

For thermoplastics, the Air Force is examining manufacturing procedures for reduced costs and improved performance, improved damage tolerance, increased design flexibility, and ease of supportability.

The Air Force also has an effort on the use of organic composites for low observability. This entails demonstrations of full-scale components and in-line service practicality.

Carbon-carbon materials are receiving special attention because of their long-life, high-temperature potential for propulsion system applications.

Ordered polymers are of special interest because of their potential for providing high-specific strength in combination with high-specific modulus.

In summary, the Air Force has a continuing interest in composite materials for aircraft systems with emphasis on material improvement, higher-temperature capability, supportability, durability, damage tolerance, and design and manufacturing technology development. Program plans have been defined through FY 1990 covering graphite-epoxy structures, ballistic survivability, laser survivability, and structures beyond graphite-epoxy.

U.S. Navy (D. Mulville)

The Navy's program stresses high-strain wings, low observability, advanced landing gears, and supportability for designs to fly in the 1990 to 2000 time frame. The program has two major elements: structural mechanics and aircraft structures technology. The division of effort is approximately 20 percent and 80 percent, respectively.

The structural mechanics activity includes impact damage mechanisms, modeling for fatigue and fracture analyses, and damage tolerant structures. Structural dynamics work includes aeroelastic tailoring.

The aircraft technology effort includes advanced design concepts, structural durability and certification, supportability (repair and damage acceptance criteria), loads and system life management, and electromagnetic compatibility and effects.

U.S. Army (P. Haselbauer)

The Army program is directed to rotorcraft and encompasses basic research, exploratory development, and advanced development covering manufacturing and processing methods and systems.

The basic research effort includes work on toughened resins and high-strain fibers for energy absorption. Projected work includes postbuckling of thin-gauge materials, coupling (structural) of composite rotors, failure criterion, and energy absorption.

The exploratory and advanced development work is directed at rotor systems (blades, hubs, and controls) and the airframe (lightly loaded structures, primary structures, and landing gears).

Work is in progress to develop damage tolerance and durability criteria for composite structures, improve fatigue analytical techniques and methodology, and develop vibration reduction techniques and analytical procedures. The results of these efforts coupled with structural component test and flight data recorder efforts will culminate in a helicopter structural integrity program for both metallic and composite structures.

The advanced development program resulted in the following accomplishments: blades with less drag (50 percent), fewer parts (50 percent), less cost (15 percent), and less weight (20 percent); a multitubular spar system; and bearingless main rotor and fiberglass rotor blade concepts. As a result of these earlier efforts, composite rotor blades are the accepted norm for helicopters. There are composite rotor blades on the CH-47D, CH-46, and AH-18, and they are soon to be introduced on the UH-1H. Product improvement programs will most likely provide composite rotor blades for the UH-60 and AH-64. Additional effort is planned to develop techniques and procedures for quantum improvement in producibility and cost reduction.

A full-scale flex-beam composite hub is under development for the AH-64 helicopter, and a whirl tower test is scheduled for mid-1987. A flight test is planned for early 1988. The flex-beam concept will reduce cost, weight, and drag while improving reliability and maintainability.

An advanced technology retractable landing gear is under development to reduce drag and provide improved crashworthiness capability. Full-scale drop tests are scheduled for mid-1987.

Initial efforts on composite tailbooms and stabilizers led to the demonstration Advanced Composite Airframe Program (ACAP). The ACAP had as its major objectives the demonstration of damage tolerance, crashworthiness, and repairability. In addition, it had the objectives of demonstrating the benefits of cost and weight savings achievable with composites, the establishment of a credible cost data base, and the reduction of risks in committing to the development of composite primary structures.

The Army program was funded at about \$25 million in FY 1986 (excluding manufacturing work).

Committee on Net Shape Technology (M. Steinberg)

Dr. Morris Steinberg, chairman of the Committee on Net Shape Technology of the National Research Council's Air Force Studies Board (AFSB), summarized the committee's activities, noting in particular the work of Workshop III, Future Composite Manufacturing Technology.

The workshop was focused on the net-shape manufacturing of composite structures as part of the AFSB's examination of net-shape manufacturing. The program covered Air Force Program Overview, Factory of the Future, Technology Issues (thermosets, thermoplastics), Metal Matrix, Carbon-Carbon/Ceramic Matrix, Raw Material, Material Forms, Tooling and Processing, Quality Control/Repair, and Carbon-Carbon for Hot Airframe Parts and Engines.

The purpose of the meeting was to identify government and industry technical and financial needs to accelerate the development and transfer of technology and its application for low-cost composite manufacturing. The questions to be addressed were: What are the drivers? What technical and institutional bottlenecks exist? How are processes and products that are reproducible and affordable to be achieved? and What should be done to accomplish this?

The field of composites evolved from the 1960s with emphasis on performance priority to the 1970s with emphasis on manufacturing methods to the 1980s with emphasis on quality control, costs, maintainability, and repairability.

Technology needs were identified as relating to: many small and medium-sized manufacturing technology programs; more technology transfer workshops to identify key technology issues and approaches to their resolution; establishment of specifications for production-ready prepregs; guidelines for assessing and repairing manufacturing defects; selective funding of automation projects; and material specifications and characteristic requirements for thermoplastics.

Manufacturing needs were identified as relating to: microprocessor controls for in-process quality control; greater interface and interaction between materials processors and manufacturers; more literature on processing science, technology, and practice; and improved data bases on materials, processing, and computer modeling.

Regarding thermosets, there are concerns over relative brittleness and the slow, costly processing of parts. The quality of prepreg hampers automation and causes problems relating to reproducibility, defects, and reduced tolerance to physical and chemical environments. Poor prepreg properties also adversely impact labor costs, rejection rates, and rework. The adverse impacts carry over to end products in the form of reduced durability and reliability, reduced design strain (some 40 percent) resulting in overdesign, and loss of potential performance and increased cost.

Regarding resin-matrix thermoplastics, they can provide greater toughness and are less expensive to fabricate while providing high-strain potential and better damage resistance and tolerance. However, these materials are relatively new to aircraft and, thus, limited experience and data base exist. Creep and fatigue characteristics, especially at high temperatures, are not fully known.

The workshop resulted in the identification of the general needs as follows:

- integration of design and manufacturing;
- better data-base and design guides;
- automation with specific attention to reduced costs, improved consistency, and reduced labor content;
- sensors that control processes, material production, and quality, and reduce rejections;
- improved nondestructive-testing techniques;
- improved curing concepts;
- tooling development; and
- improved repair techniques.

The workshop is to produce road maps for a program (including program costs) that will increase composite net-shape productivity and cost-effectiveness.

INDUSTRY FORUM OF FEBRUARY 10-11, 1986

Large Transports

Boeing Aircraft Company (J. Quinlivan)

Composites have been and are applied in many nonprimary, important parts on current transport aircraft. At Boeing, some 300,000 pounds of composites per year are used in production aircraft. Damage tolerance is a critical concern and requires extensive testing.

Boeing is examining the use of composites for primary structural components (wings, stabilizers, and aft fuselage body) as well as for secondary structures. The new JVX (tilt-rotor) aircraft will be essentially an all-composites aircraft.

Inhibiting factors relate to costs of manufacture as well as the production facilities themselves. However, progress is being made on cost reduction. At present, in spite of greater costs for materials and tooling for a composite wing, it is estimated that a final cost would equal that of an aluminum wing. Other inhibiting factors are: material limitations, design and certification uncertainties, and the levels and amount of testing required.

Compared to present conventional composite design, the proper application of advanced composites can reduce costs by some 20 to 30 percent through reduced parts, weight, and production and increased strength.

Further cost reductions should be possible through innovative design, the use of computer-aided design and manufacturing (CAD/CAM), and automated production. In the future, thermoplastics should have a role. The outlook is for composites to become some 60 percent of the total airframe by weight by the late 1990s.

Although new organic-matrix composite materials show much promise, they are not well understood from behavior and performance considerations. An important consideration is the ability to verify analyses by testing.

New organic-matrix composite technology developments need to focus on fuse-

lages, empennage, and wing applications addressing matters important to operations such as damage tolerance, repair, durability, flammability, fire and lightning protection, and electromagnetic effects. Other important matters related to design and production include joints, cutouts, impact dynamics, acoustics, and postbuckling integrity.

Certification is a significant issue. The Boeing philosophy is "certify by analyses supported by test evidence." There is a need to advance analytical techniques to handle the technical matters noted and to reduce test and certification time and costs. The analytical tools must handle both macro- and micro-engineering assessments. Just as important is the development of simple, consistent, standard test methodology that can assist in proof-of-design analysis and cover such matters as load distributions, large deflections, accelerated testing, failure processes, effects of environment spectra, and residual strength after failure.

Technology development is needed for integrated thick and thin structures that cover understanding of materials and, more importantly, effects of processing, design methodology, damage tolerance assessment, prediction of and assessment of allowables, and response to service environments.

McDonnell Douglas Corporation (H. C. Schjelderup)

The introduction of composite materials in commercial aircraft structures has been slow compared to their introduction in military aircraft. Flight service components, such as the Boeing 737 spoilers and the Douglas DC-10 aft rudder, have been in commercial airline service for over 10 years without any serious material problems. As a result of these and other flight service programs and NASA-sponsored research, composites are in production for the Boeing 757 and 767, the McDonnell Douglas MD-80, and the Airbus 310.

Most composite design and manufacturing engineers support the position that the state of technology allows production commitments to all structural components except wings and fuselages. For these two primary structural components, differences in opinion center around damage tolerance and manufacturing cost; not that a wing or fuselage could not be designed, but will they be structurally efficient and economically justified. Recently NASA terminated fuselage and wing technology development programs that could have helped resolve design questions about such structures.

Douglas uses classical numerical and semiempirical methods of analyses appropriate to the class of structural system problems being addressed: predominantly simple and elastic in nature; large and complex; large displacements; many variables; and/or strength and fracture dominated.

Design and analyses are supported by material characterization programs for every new material used in production. Representative data developed include qualification and allowables for strength and elastic properties, environmental effects, fracture properties, and bonded- and bolted-joint properties. All composite sub-assemblies are inspected for voids, porosity, inclusions, and delamination by avail-

able techniques. New techniques for nondestructive testing are under study, i.e., backscattering, leaky Lamb waves, and computer analyses.

Emphasis is being put on raising design strain levels while holding stiffness to make composites more competitive for primary structures.

Current Douglas composite designs operate at low-stress levels to increase damage tolerance. To date, testing (coupon and subsystem) does not indicate a limit to the life of operational structures. Accelerated testing is limited. It cannot be used where friction overheats components or where certain types of failure modes could be missed, i.e., creep-rupture. Compressed real-time testing is used in such structures.

Experience shows that the following technology development should be pursued for heavily loaded structures: *compression failure*—associated with laminated structures with out-of-plane (transverse) loads; *tension failure*—associated with strength but more importantly with edge (delamination) failure; *interlaminar failure*—associated with thick, heavily loaded structures and, in particular, with out-of-plane stresses; *joint analysis*—addressing load distribution among bolts, induced transverse tension associated with combined loading, combinations of orthogonal and bolt loads, and automated handling of finite analyses of bolt combined with in-plane loads; *hydrothermal stress*—associated with heat and moisture in the production process, a problem for thick laminates; *damage tolerance*—for large complex structures considering the application of finite element analysis through development of orthotropic, elastic-plastic, crack-tip, and delamination elements (the mechanisms of crack or delamination propagation) and analytical techniques for applying the results of coupon and panel tests to full-scale components.

Because testing is time consuming and expensive, effort is warranted on developing semiempirical approaches to analyses to reduce the need for extensive testing.

Wider, more extensive use of composites is inhibited by a lack of applied experience. This causes unknown performance, schedule, and cost risks. It is believed that the technical risks are reasonably known and solvable but producibility and production costs and scheduling are not. Costs are a significant commercial development deterrent. However, there are positive drivers for composites: reduced weight, corrosion, and fatigue; lower costs (potentially); and the ability to tailor the structure elastically. Tailoring, the ability to change structural characteristics in all directions, is a major and beneficial difference between composites and metals.

Damage tolerance in primary structures for commercial aircraft is a major concern requiring an ability to assess fully any nonvisible damage. Currently, Douglas uses the "MIL-Prime" damage tolerance criteria for composite primary structures (under development by the Air Force). The FAA has yet to develop damage tolerance criteria for composite structures, such as wings. The establishment of such criteria will require evaluations of damage sources, inspection intervals, and damage tolerance properties.

Thermosets and thermoplastics both have future roles. At present, the use of thermoplastic is inhibited by high costs and the need to develop technology

related to such matters as joining, repair, creep, solvent sensitivity, and automated manufacturing.

The technical barriers to wider use of composites include:

- Damage tolerance (and its predictability). Additional research is warranted related to safety of flight—a first-order issue.
- Electromagnetic effects. Due to the low electrical conductivity of composites, the designer has special problems—lightning protection, electromagnetic interference, antenna design and performance, and electrical hazards for personnel.
- Material data base. This is a difficult issue because of the “no limit” of materials, their combination, and their processing. An industry standard for materials property testing is required for the development of handbook data. Related problems involve keeping the standards current and the introduction and acceptance of new materials.
- Analytical tools. These are generally good but not always adequately applicable to through-the-thickness forces without very complex finite element modeling. A valuable addition would be three-dimensional, laminated-element techniques to characterize such forces.
- Adhesive bonding integrity. Bonding is very process and preparation sensitive. There is a need for ways to simplify and assure process integrity and quality.

The technology development needs that are most critical to commercial transport development relate to program cost. It is believed that technical and engineering issues can be resolved in development programs. A valuable contribution would be the generation of design, production, and process cost models for representative designs.

As to the question of NASA support of FAA certification activity, it is not recommended that NASA be directly involved unless asked for expert advice. However, NASA is encouraged to increase its large-structure feasibility work and to continue its R&D programs with industry and university involvement. Timely government involvement and support for basic R&D oriented activity is particularly important from competitive and military considerations. Effective data dissemination is also an important government role and would serve to minimize duplicative and expensive work within industry. The government should also support high potential payoff work that is beyond the ability of individual corporate R&T programs to support.

Lockheed Corporation (R. L. Circle)

For technologies in transition there are three kinds of forces that can accelerate their application: improved performance, reduced costs, and the political environment. Composites present a real challenge since they require major changes in the design, development, test, manufacture, and operation processes.

The application of composites in fighters is driven by the potential for performance improvement. The same is true to some degree for bombers. The driver for transport aircraft is cost, initial and life-cycle—that is, lower costs with particular

attention to low development risk. Today, there are fighters with composites making up 30 (and going to 60) percent of the airframe weight, including primary structures. For transports, the number is some 3 percent with continued application to secondary structures and the potential for some application to primary structures.

The technology issues associated with scale-up and materials from fighters to large aircraft (bombers and transports) are significant. Differences concern structural design and the amount of material to be processed, some 1,300 pounds versus 100,000 pounds of composites, respectively.

It is clear that the Europeans are making significant commitments to using composites in transport aircraft. The most aggressive application has been in the 70-passenger ATR-72 center wing box.

The introduction of composite primary structures to transports will depend on a clear understanding and response to what the industry sees as the issues related to a full commitment. There must be confidence that the payoffs warrant the risk. This requires an adequate technical data base, the ability to project costs accurately, and reasonable assurance that contracted schedule, cost performance commitments can be met. Therefore, technology development programs that demonstrate and validate the technology and performance are required to allow sound cost trade-off assessments.

Lockheed's operating experience with composites (C-141 wing, leading edges, and petal doors) has been good. The costs for manufacturing these parts are below those of metal parts, even though the composite parts were essentially hand lay-ups. As part of NASA's Aircraft Energy Efficiency program, Lockheed designed a composite L-1011 vertical fin. Based on this experience, the importance of tying design and manufacturing closely together was clearly demonstrated. It was projected that through parts reduction and automation the cost of the composite fin would be \$133,700, compared to \$195,500 for a metal fin.

The NASA program approach to assist industry (i.e., soliciting ideas from industry, funding studies to define critical technology, coordinating industry technology development and validation, and emphasizing technology transfer) is strongly endorsed and should be continued.

The NASA/Lockheed composite wing program for large aircraft has been restructured because of funding reductions in the NASA systems technology program. The new program eliminates all validation work and concentrates on design optimization, innovation, new materials, and fabrication methods for such wing elements as covers, spars, stiffeners, planks, and fuel containers.

This restructured program will not provide the level of confidence desired for a full commitment to the application of composites to large primary wing structures. There are other programs that will help build confidence: Air Force Materials Laboratory (AFML) large fuselage and manufacturing technology (MANTECH), V-22, and the advanced technology bomber. However, these programs collectively fall short of providing and validating the technology data base for large transport aircraft. Another problem is that there is no dedicated effort directed at industry-wide technology transfer from these limited programs.

New programs are needed that:

- Give adequate attention to innovation and apply the unique characteristics of composites;
- Do not duplicate metal designs;
- Direct attention to the integration of manufacturing into design;
- Include full-scale design and performance validation; and
- Assure industry-wide technology transfer.

The new program should: address transport wings and be jointly supported (NASA/AFML); include full-scale validation work (NASA—design, materials, and analysis; AFML—tooling, manufacturing, costs); emphasize low-cost, low-risk, operational supportability and design-manufacturing innovation; and develop new analysis and test technology.

Rotorcraft

Bell Helicopter Textron (K. Stevenson)

The use of composites in rotorcraft development has been more aggressive than in conventional aircraft. Today, designs incorporate some 8 percent metal. The use of composites is almost complete, having been applied to rotor blades and hubs, fins, landing gears, pylon supports, fuselages, and, in the case of the V-22 tilt rotor, the wing. This has been driven by military requirements for higher performance and increased operability, both dictating lower weight and improved supportability. These requirements demand stiffness, tailoring of natural frequencies, crashworthiness, lightweight materials, and damage and ballistic tolerance. These demands are met by composites.

The application of composites to rotorcraft has proven very effective. One significant advantage is the ability to tailor stiffness, load path, and failure modes. Composites also reduce corrosion, weight, cost, and fatigue failure. Filament winding, honeycomb-core tape wraps, and bonding have been used with success. Materials include fiberglass-epoxy and carbon-epoxy tape (T300/788).

Future technology development should concentrate on easily utilized analytical techniques for design, material specification standardization (companies use different specifications), development of consistent approaches to specifying allowables, and standards for nondestructive inspection (a big problem).

Boeing-Vertol (C. Albrecht)

Rotorcraft are weight, fatigue, vibration, and control critical and have much less constancy of structure than conventional aircraft. Many of the response characteristics of a rotorcraft are not known, definable, or understood until flight because of rotor-imposed loads. With the maturing of the industry, design philosophy is changing. Earlier designs emphasized safe-life, with some 58 percent of the dynamic component weight dedicated to safety. Present design philosophy emphasizes

TABLE A-1 Performance Comparisons of Metal and Composite Rotor Blades

	Navy		Army
	Metal	Composite	Composite
Mean-time before unscheduled removal (hours)	135	2,050	1,500

damage and defect tolerance, with dynamic component weights of some 80 to 85 percent dedicated to multiple load-path capability and some 10 to 15 percent single load-path capability.

Work on composite rotor blades started in 1957. The decision to use composite blades for production systems was made in 1970. Through late 1985, Boeing-Vertol had no failures of these blades, compared with 17 metal-blade failures over the period 1962 to 1973. Performance of metal and composite blades can be assessed in Table A-1 from Navy and Army data on mean-time (hours) before unscheduled removal. Cost has favored composite blades over metal blades by a factor of about 1 to 2 on the basis of manufacturing man-hours per pound.

A decision was made in 1981 to use composites for all possible elements of the dynamic system on Boeing-Vertol's twin-rotor Army 360 aircraft. This involved blades, hubs, rotor shafts, transmission covers, and pitch housing. The resulting weight savings was 1,394 pounds (17 percent) over the metal system. All of these composite systems are being tested.

In Boeing-Vertol's experience, composites have shown the following failure characteristics: fiberglass—soft, slow, detectable with a low sensitivity to notch fatigue; graphite—unacceptable modes for critical components; and hybrids of fiberglass and graphite (50-50 percent)—soft with stiffness and tailoring flexibility. Composite-blade root ends have been shown to have high damage tolerance in tests with damages imposed after 4×10^6 cycles at design loads. Other parts have shown high tolerance to damage and fail-safe capability with careful design.

Composites have also shown good fatigue life in a rotor shaft application with a design that weighed less than an aluminum shaft and considerably less than a steel shaft. A composite application to an advanced rotor hub resulted in a structure having 25 percent less weight, 60 percent fewer parts, and 60 percent fewer maintenance hours.

The company has set its own general design objectives for composites for flight-safety-critical rotorcraft components:

- Fiberglass for damage and defect tolerance.
- Graphite for stiffness to a limit of about 50 percent.

- Fiberglass to sustain limit loads.
- Basic structures are to take ultimate loads without fiber failure and limit loads without interlaminar failure.
- Basic structure mean 2-sigma fatigue strength should exceed maximum anticipated steady-state vibratory loads.
- Basic structural life should be in excess of 10,000 hours based on 3-sigma allowables with "soft" observable damage tolerant failure modes.

Composites are used for 360 airframe components; fuselage, flooring, fore and aft transmission, landing gear, and engine supports. The benefits are 25 percent in weight savings, freedom from corrosion, a 45 percent reduction in recurring costs, and a 90 percent reduction in tooling costs. The frame, stringer, and panel design has been substantiated by static tests that will be followed by shake tests to validate NASTRAN analyses. At 5,017 pounds, the weight saved over a metal structure is estimated to be 1,389 pounds (about 22 percent).

The rotorcraft industry has applied composites with considerable success to high-cycle, fatigue-loaded primary structures. Composites can provide characteristics (soft failure, damage tolerance) for safety critical components not possible with metals. Increased life is realized because of high fatigue to ultimate strength ratios.

Additional research should be conducted with hybrid structures for safety critical components. This includes improved analytical capability especially for complex, thick-laminated dynamic structures. Generic research should be pursued for optimization of design and development of design guidelines to account for creep relaxation in fits and clamps.

An issue is how to test under high-frequency loading. Needed are test and analyses techniques that can account for cumulative damage and sequential loading of safety critical components. More needs to be done to understand the propagation of defects associated with long-term, low-amplitude, high-frequency disturbances for both fixed and dynamic components.

In addition to complex analytical tools, the industry needs simple, quick design tools for preliminary design and analyses. The industry also needs design guidelines for controlling failure modes. A related matter is crashworthy design concepts for primary structures.

Work is needed to develop a better understanding of environmental effects (hot/wet) on thick composite structures used in dynamic systems.

To get costs down, close interaction and optimization is needed between engineering design and manufacturing.

Much of NASA's composites research and technology development work has been directed at systems designed for static strength and low-cycle fatigue. To assist rotorcraft, the research and technology development should include three-dimensional structural analyses, mechanical attachments, joints and lugs, fatigue-life analyses techniques, high-cycle fatigue effects, simple rapid techniques for preliminary design, failure mechanism control, crashworthiness concepts, and environmental effects on thick components.

McDonnell Douglas Helicopter Company (R. M. Verette)

The company has had a long involvement with composites in rotorcraft. McDonnell Douglas Helicopters (formerly Hughes Helicopters) used mostly fiberglass epoxy for the Model 500 and Kevlar epoxy for the AH64A Apache. Parts production has principally involved 250°F curing materials and a range of conventional manufacturing processes.

Research and development programs have included landing gears, crashworthiness, tail and main rotors, pitch cases, flex beams, tail booms, and vertical and horizontal stabilizers. The program has included element level tests as well as selective flight tests. The company has experience with filament winding and with graphite as well as Kevlar and fiberglass epoxy systems.

The company is making a major investment in a new plant at its Mesa, Arizona facility. Of the 340,000 square feet in the Advanced Development Center, 65,000 square feet will be devoted to composites and will be outfitted with existing and new equipment.

Recommended future actions include generic work to identify (characterize) the best materials and processes for particular applications considering such factors as cost, schedule, and quality of product. Included in this work should be such matters as automation, processes (including co-curing), computer-aided design and manufacturing, CAD/CAM utilization, and product property improvement. Tooling, in itself, warrants study. Matters such as initial and life-cycle costs, production lot size influence on tooling materials, adaptability, and life are important considerations.

For technology development, full-scale tests are essentially mandatory, i.e., for crashworthy prediction, design, and performance correlation.

Nondestructive evaluation techniques still warrant technology work. Techniques are needed that can be used with all types of composites (Kevlar, carbon, fiberglass, and new resin systems). An important consideration is using nondestructive evaluation techniques that operate at production line rates in conjunction with the production line.

Toughened resin systems have a real future. Work should focus on the compatibility of the fibers that will be applied. Thermoplastics for secondary structures should be included in future generic technology development programs. They have other than strength benefits, i.e., shelf life and cost-effectiveness for appropriate applications.

Sikorsky (B. Kay)

Composites are being used in current designs (some 10 to 20 percent of airframe) with good results. The new S-76B rotorcraft will make relatively good use of composites. A basic issue is productivity with consistency. Fundamentally, composites reduce weight, parts, fasteners, and tooling for manufacture. These are forceful drivers for more extensive use of composites.

Sikorsky is working with an Italian firm on the production of an all-composite fixed-wing aircraft, the composite structure being the Sikorsky contribution.

The lack of material data bases is of concern. Although analytical techniques are essentially adequate, more technology development is very desirable especially for the handling of complex loading cases and complex structural systems. Rotor heads are an example where improved design and analytical techniques would be very beneficial as would be better materials for such high-stress components. Sikorsky's experimental all-composite rotorcraft flight test program was accelerated (with limited component testing) to speed up the validation of the design, provide early cost data, and hold program costs down. This is not a universally suggested approach given the present state of experience with all-composite design.

It is recommended that attention be directed at the use of universities for expanding technical knowledge; training professionals in the field of composites from design, development, manufacturing, and test considerations; and the standardization of analyses, testing, and materials. The latter, it is recognized, will be difficult because of the broad range and changing nature of materials.

High-Performance Aircraft

Grumman (R. N. Hadcock)

Organic composites development work started at AFML in 1964 and was applied to a Navy F-14 horizontal stabilizer (boron epoxy) in 1969. Since 1970, structural composites have been used on U.S. fighter and attack aircraft for empennage and wing covers. The AV-8B aircraft has its wing and much of its fuselage (some 28 percent of the structural weight) made of composite material. Many aircraft of foreign design make extensive use of organic composites.

The early aircraft employed boron-epoxy materials. This material gave way to graphite-epoxy materials because of costs and improved design latitude. The lower weights possible have been translated into smaller, lighter, less expensive, higher-performing aircraft. For the same payloads, studies show that with about 70 percent of the structural weight in composites there can be a 22 percent reduction in takeoff gross weight compared with a metal aircraft. However, in advanced fighter and attack (high-performance) aircraft, two issues restrain broad use of composite materials: affordability and the ability to operate at high (elevated) temperatures.

For these expensive aircraft, the high cost of materials is less of a deterrent to their use than for less expensive aircraft. Even so, material costs (which can be 10 to 15 percent of the airframe cost) are not significant. Compared with aluminum, titanium and the organic epoxies are some 8 to 10 times more expensive. In addition to the costs of materials, the cost of design, production, test, and certification must be factored into the total cost of an aircraft. In general, these are more expensive activities for composite than for metal aircraft, with the possible exceptions of assembly, maintenance, and operations support.

The cost of most high-performance aircraft has held steady in total fly-away price, in constant dollars, but have increased in dollars per pound empty weight. However, the price is too high and may well stay high at the low production rates

experienced this past decade. The question raised with regard to low production is: if a surge in production is needed to respond to an emergency, what are the implications for composite material production and application?

A major effort is required to quantify and reduce costs associated with composite materials, i.e., innovative designs for automation, low-cost manufacturing, quality assurance of material, manufactured parts and systems, and improved reproducibility and repairability. Tool design and quality are also important.

For advanced high-performance aircraft designs, higher-temperature operations are required. Current epoxy-matrix materials are limited to service temperatures of 260°F. Bismaleimide- and polyimide-matrix composites and metal-matrix composites can be operated at higher temperatures, 550°F and 1,200°F, respectively, but they are expensive. Ceramic-matrix composites hold out promise for operation at up to 4,800°F with protective coatings. This arena requires considerable work that needs to start now if the conceptual supersonic and hypersonic aircraft of the twenty-first century are to be realized. There is no question that this represents a large future for structural composites (organic, metal, and ceramic).

Current problems with the application of organic composites include: variability of materials, processes, final geometry, and strength. Wide use of composites is inhibited by costs, inspectibility, schedule uncertainties, risk, and investment. Analytical tools are not show-stoppers, but better tools will reduce cost, weight, and development schedules and equate to improved vehicle and program performance.

The drivers for greater use of composites are weight reduction, performance improvement, corrosion resistance, low observability, and survivability.

Thermoplastics have a definite role in the near term for substructures and secondary structures. As for thermosets, costs need to be reduced.

Technical barriers to broader use of organic composites relate to:

- Material variability;
- Costs from design to certification and support;
- Lack of data bases and approved specifications, standards, and design allowables;
- Inadequate cost bases for investment; and
- Lack of confidence in new technology.

There is a need to characterize and standardize material data bases and element testing. Analytical tools, though adequate overall, need improvement. Testing techniques, the "building block" approach, have been adequate.

The barriers to bonding relate primarily to secondary joints where there are problems with variability of parts, fit-up, inspection, nondestructive testing, high-temperature adhesives, and out-of-plane loads.

Recommended actions include:

- Standardization of such factors as materials and process specification, design properties, analytics, testing techniques, certification procedures, and high-temperature materials;

- NASA support of FAA certification activity to develop uniform procedures and ground rules;
- Government laboratories should do some work in material synthesis but also sponsor industry effort;
- Government should support multiple-award R&D programs and high-risk innovative technology developments, and should provide better mechanisms for transition into production.

It is projected that the next generation of high-performance aircraft will use some 35 to 45 percent composites by weight of the airframe. As noted, this can be translated into smaller, lighter, less costly aircraft for a given mission compared with an all-metal aircraft. There are no show-stoppers for service temperatures up to 350°F (sustained speeds of M 2+). Greater use of composite materials are inhibited by affordability, temperature capability (beyond 800°F), and standardization of materials, processes, and testing. Standardization is very important to facilitate communication between activities within an organization as well as between organizations.

Rockwell International (L. W. Lackman)

For the B-1 aircraft program, Rockwell is using composites for structures at a rate of about 400,000 pounds per year. The tooling and handling processes are automated to accelerate production and for consistency.

The company has invested significant contract and in-house funds to develop data bases and analytical tools. At Rockwell the composite R&D effort began in 1965 (T-39 wing box) and continued with component and test technology of a generic and specific nature up to work in 1985 on leading edges, large aircraft wings, and B-1B components. About \$100 million of Rockwell and government funds has been invested in this work. About \$30 million has been invested in developing a composites test data base. This involved flight certification and materials characterization work using coupons and elements, and full-scale tests for static, fatigue, temperature, and environment and service test conditions. The material characterization work has resulted in the preparation of an advanced composite design guide based on approximately 15,000 tests. Rockwell's standards and allowable design strain levels for composites are incorporated in this design handbook.

The B-1B composite components (flap, wing pivot fairing, rotary launcher, weapons bay door, and wing movable fairing among others) have undergone static and fatigue tests.

Rockwell has on-hand many of the computer programs needed for composite applications analysis. They were generated by Rockwell and others and cover such matters as: point stress; bonded symmetric-stepped laminate characterization; moisture absorption; design-stiffened, skin plate, wide column optimization; aeroelastic tailoring; and structural optimization.

Standard ultrasonic and x-ray as well as "coin tap" and visual nondestructive-testing techniques are used to validate manufactured articles. However, these techniques are not suitable for thick or complex structures. The latter require (undesirable) hatches and holes that still may not provide appropriate access.

A building-block approach to certification is used that covers the issues of lifetime prediction and accelerated testing. A key to this approach is for each building block to have the same type of failure mode as the blocks grow in complexity.

Because of the benefits associated with all bonded structures—structural integrity, lower weight (about 10 percent), lower manufacturing cost (about 15 percent), and reduced fuel leakage—Rockwell is committed to bonded, integral composite wings for future aircraft. Design must consider inspection, damage containment, battle damage, and production rate and supportability.

Experience has shown these matters to be problems: out-of-plane loads—difficult to predict, need good modeling; effects of impact damage on compressive strength—an empirical process, need better analytical tools; environmental effects—though generally understood, need careful design attention; bearing interaction allowable strength—tools for analyses reasonably in hand; bonded-joint thermal mismatch—a serious issue in need of attention; variability of bonded-joint quality—design approaches and validation techniques needed; and durability and damage tolerance prediction—a real problem, need prediction techniques since analytical tools are not available and designers are forced to depend upon testing.

The factors that inhibit wider use of composites include: initial acquisition costs of tooling; limited service temperatures; integrity of bonded primary structure joints; areas of high-load transfer—designers use metals since they handle concentrated loads better; supportability requirements—difficult to identify and estimate costs since good models are not available; sensitivity to low-level impact damage; and effects of hostile threats, such as from lasers—need to be examined. Also of concern are tools to allow reasonable analyses of flaw growth and life prediction, postbuckling failure characteristics, and out-of-plane strength prediction.

The factors stimulating interest in composites are: lower weight and cost (15 to 25 percent versus metallics); lower part counts; aeroelastic tailoring; and reduced radar signature. Full appreciation of composites will come only with design approaches that do not follow metal practices by making best use of composite characteristics.

There is a place for thermoplastics but more technology development is needed. If they are to be used for high-temperature applications, new materials are needed. It would be very desirable to characterize, across the industry, the material data base. There is a need to start now to standardize specifications and test procedures. This needs to be accompanied by standardized procurement, processing, and testing specifications. There would be a real payoff with this activity.

Technical barriers to the application of composites include the establishment of out-of-plane failure criteria and improved methods of analyzing joint-load distribution, and techniques for testing impact effects, battle damage, and standardized specimens.

For adhesive bonding, the major technical barriers are considered to be design confidence, thermal mismatch, and surface preparation requirements. These can be resolved through additional PABST-type programs with elevated temperature (350°F) materials, use of lower thermal expansion materials when bonding metals to composites, and improved process control.

It is recommended that the government continue to play a key role in enhancing the technology data base where there is high risk associated with new materials and manufacturing techniques, in developing the technology prior to production application, and in transferring technology. Government and industrial teaming is a good way to build the data base and transfer the technology. In this regard, it is important that the DOD also give attention to the technology transfer problem. Here, technology transfer meetings and teaming will be of real help. Continued university involvement is encouraged.

The development of professionals for this growing area would be helped by expanding university commitment and participation, increasing company-sponsored training, and using professional societies for such matters as setting standards and test procedures.

Lockheed Corporation (J. B. Hammond)

For the 1990s, there will be a mix of metals and composites. A systems look at design is required to get the best mix for maximized fleet effectiveness. However, there will be a high percentage of organic composites, with metals in appropriate places, approaching 50 percent by weight and providing some 20 to 25 percent structural weight reduction.

The nature of the future factory will change. With the move from aluminum structures to current composites, there was an increase in attention to materials and fabrication. With more advances in composite applications, attention to materials will increase as will attention to assembly, particularly to material quality and quality control, and automation. The factory will handle a mix of materials: composites, titanium, and advanced aluminums. This will tend to increase factory complexity and costs. However, it is believed that composite structure fabrication and labor cost-saving techniques can result in an airplane with significant composite content that will have costs equal to that of an equivalent all-metal aircraft.

Carbon-fiber-reinforced matrix system program drivers are thermoplastic systems for up to 350°F to 450°F, high modulus/strain fibers and tough epoxies, and high-temperature systems. The higher-temperature thermoplastics promise low manufacturing costs and supportability improvements, but technology readiness requires significant additional effort. A possible, important composite design problem relates to the ability to handle cyclic loads.

Work shows that cooling rates for thermoplastics can have significant effects on material characteristics and can be used to modify materially the characteristics. Thus, more work to develop a fundamental understanding of material parameters and their influence on processing and finished-part structural behavior is indicated.

Variables include fiber type, pretreatment and degree of bridging, thermal cycling, processing, and interphase morphology.

Thermoplastics will require barriers for fuel containment but this can be handled. Thermoplastics are of interest for reasons other than relative ease of formability. They are reformable, can be fused and welded, and waste material can be reused. To take advantage of these characteristics, however, will require work to increase toughness and manufacturing flexibility and to reduce costs.

The technology development needs for both thermosets and thermoplastics include tough high-temperature resin systems that are compatible with high modulus/strain fibers, can be automated, and can be cost-effective. Thermoplastic technology development needs to encompass optimal resins, surface-coating adhesion and adhesives, development of qualification test parameters, and identification of low-cost manufacturing processes.

The basic composites issue is the ability to get low-cost structures that satisfy system performance requirements. Accelerating the development of thermoplastic technology with emphasis on costs and productivity would help achieve this. In general, there is a need for better, common-specification analysis and test methodology, and methods for handling out-of-plane loads. NASA should pursue this basic work.

McDonnell Douglas Corporation (E. D. Bouchard)

McDonnell Douglas has a major commitment to use composite materials. With these materials, it has been possible to contain aircraft structural weight while meeting more demanding performance and supportability requirements on the F-15 (Eagle), F-18 (Hornet), and AV-8B (Harrier II) aircraft. The composite structural weights of the F-15, F-18, and AV-8B are 1, 9, and 26 percent, while the number of composite parts and assemblies vary from 16/7 to 145/59 to 502/25, respectively. The estimated structural weight savings are F-15, 24 percent, and F-18, 18 percent. For the F-15, the major composite applied is boron epoxy for the vertical and horizontal tail torque boxes. Carbon epoxy is used for the majority of other composite parts. Carbon bismaleimide is used to a limited extent in the AV-8B aircraft. The rest of the composites are carbon epoxy. To date, over 90,000 detailed parts and 30,000 assemblies have been delivered for service aircraft.

Sophisticated analytical techniques are required for successful development of design features such as wing root joints, cutouts, local hot spots, and wing skins. Critical areas require extremely fine grid modeling.

The key to expanded use of composites and exploitation of higher-strain levels is the continued development of analytical tools that include automated design and analysis methodology.

As noted, organic composites are used extensively on AV-8B aircraft. This includes carbon epoxy, fiberglass epoxy, carbon/BMI, and fiberglass/BMI. On this airplane, carbon bismaleimide is used in the strakes that are exposed to the hot exhaust gases during hovering flight. The wing skins are mechanically fastened to

spars and ribs that are corrugated. A major portion of the wing serves as an integral fuel tank.

Structural testing of the composite parts has been and still is an area of major concern, but is not an insurmountable problem. The success of these composite programs depended on extensive, thorough design and preproduction testing from coupons to components to structural assemblies. Structural testing of composite parts has been and still is an area of major concern.

The McDonnell-Douglas commitment to composites will increase material demand. Today, some 1,500 pounds of composite prepreg is used daily.

Experience has shown hard tooling to be a good investment. Inexpensive "soft" tooling has resulted in serious manufacturing problems. One cost-effective, hard-tooling concept is electroformed nickel faceplates supported by lightweight steel frames. Though tooling can be expensive, integral molding of parts saves many labor hours and has resulted in net cost savings.

Successful production experience requires a serious commitment to facilities and equipment. In addition automation of manufacturing methods, inspection procedures, processes, and tools are mandatory for cost reduction.

In the long-term, expanded utilization of organic composite structures offers significant performance gains. Enhanced automation coupled with innovative design and manufacturing approaches can provide substantial cost reductions. Government agency support of related research and technology is considered highly desirable.

In future programs, trade studies must be performed that examine life-cycle costs with appropriate consideration for the benefits offered by composite materials. Fatigue, environmental effect, and other operational factors are significant considerations.

Specifically, technology needs to address high-strain/low-density fibers, tough resin systems, high-temperature resin systems, integrated structural analysis codes, improvements in adhesives, reductions in material and fabrication costs, and exploration of thermoplastic potential. In this work, it is important for the government to maintain a competitive environment and to examine competing systems, including metals and metal matrices.

Boeing Military Airplane Company (J. E. McCarty)

We will see continued, expanded application of composites to aircraft. However, continued technology development can bring significant improvements; of particular interest is improvement in efficiency of application. One concern is the proliferation of new materials.

Boeing's current programs address thermoplastics, damage tolerance, survivability, repair, analytical techniques, and manufacturing.

The Navy's A-6 (Intruder) wing replacement program is providing valuable experience in the application of composites (IM6/3501-6 graphite epoxy). The wing, a primary structure, is of typical multispar construction with a wing fold mechanism.

Thermoplastics work for the Air Force concentrates on polyetheretherketone

(PEEK) and high-temperature materials, and will result in the fabrication and flight of a flap on an A-10 (Thunderbolt) aircraft. The materials used will be characterized, but this will not constitute a material data-base program.

The R&D work on damage tolerance includes development of a set of requirements for Air Force aircraft, an assessment of analyses for flight safety critical-damage evaluations, and development of analyses for assessing impact damage and resulting residual strength. In support of this work, a multispar rib box is being constructed for testing.

Thermoplastics is a key effort at Boeing. The interest in thermoplastics is twofold—higher toughness and the potential for lower costs. Special emphasis is directed at high-temperature systems with special interest in material forms, resin-based failure, processing, and through-the-thickness analysis including impact damage and effects.

Analysis capability is considered important and is being pursued. At present, ply properties are used to establish laminate modulus and testing, to define failure strains or stresses and allowables at the laminate level.

A good data base has been established on the following thermosets: primary structure 350°F cure graphite epoxy AS4/3501-6, T-300/934, T-300/5208, and IM6/3501-6. A larger data base is needed for thermosets. This will be developed once material is selected.

Because of the commitment to composites, there is a significant effort focused on expanding the use of organic composites. This expansion is through attention to materials, design and analysis, and manufacture and quality control.

Regarding materials, there has been significant improvements in fiber-strain and failure capability. These are important matters to pursue because of the favorable impact they have on weight, design flexibility, and cost. Improvements in resin toughness are also important. A better understanding of fiber-resin interfaces is needed to take full advantage of component improvement.

An important aspect of the cost issue is manufacturing tolerance. A broadening of tolerances will be reflected in reduced costs. Standardization of materials and processes including testing could help considerably in cost reductions. Industry should collectively address these matters.

In design and analysis, as has been noted, the following need more attention: through-the-thickness analysis, residual strength after impacts, and resin-dominated load paths. Increased effort is also required to provide the tools for addressing multimode failure, interlaminar allowables, the modeling of secondary loads, and life prediction. Regarding life prediction, there is essentially no capability at all; special attention is needed now.

There will be a high payoff in manufacturing and quality assurance if attention is given to: lay-up automation, preprocessing control (checks before problems and errors are built-in), postprocessing inspection, standardization (especially for clips and brackets, where there is a potentially large business), and allowance for some reforming of components to fit varying designs. All of this will help cost reduction.

The matters that inhibit fuller use of organic composites include: labor, material,

and facility costs; the costs of obtaining and maintaining adequate data bases; the costs of compliance to specifications and certification; the brittle nature of the materials and sensitivity to damage; and the shortage of experienced and qualified engineering and shop personnel.

Honeycomb is a good design concept but it acquired a bad reputation. DOD has taken the position that it should be avoided. What is needed is a good design-acceptance criterion.

The government has an important and significant role in accelerating the utilization of organic composites. There are two aspects to this support: (1) high-risk, long-term technology developments (i.e., thermoplastics, innovation, and program acceleration), and (2) technology transfer (i.e., more focus on collection and exchange of data at the macro and micro levels). This is not effectively accomplished today. Two specific questions related to bonding need to be addressed: What is a strong bond? and How can wide-area bond separation be detected?

The government should, as part of its activity, support basic technology improvements in analytics, materials, manufacturing (including process impacts), and quality assurance methods as well as data-base development and standardization especially for new, developing materials and their fabrication techniques. MIL Handbook 17 provides a good start on a data base. Industry should support this effort.

In summary, the fundamental tools for design exist, but they need improvement to allow full utilization of the inherent characteristics of composites. Often problems are "designed around" rather than resolved because of the lack of the ability to understand and handle them. For preliminary design, "quick" design tools would be very helpful. Cost is a major deterrent to expanded use of organic composites. What is needed is continued development of the technology across the board to maximize utility and reduce costs.

General Dynamics (C. F. Herndon)

The principal issue being addressed is composite material toughness for next-generation, high-performance aircraft. These aircraft may well see composite structural weights in the range of 40 to 60 percent of the total structural weight. However, some current materials are too fragile for economical handling and processing. Future growth in the application of composites for high-performance aircraft depends on material developments and processing that result in tougher structural systems.

Experience from the 1970s and 1980s has proven the role of composites in high-performance aircraft. The question is the degree of their further practical application.

General Dynamics, in its application of composites, has had extensive, successful experience on the F-16 (Falcon—1,600 ship sets manufactured and 1,500 aircraft delivered). Over 1 million flight hours have been accumulated on this aircraft, with some having flown in the 1,000 to 2,000 hour range. The vertical stabilizers on these aircraft use thick, relatively flat laminates that are blind riveted to aluminum structures with bonded graphite spars and graphite laminate skins, and rudders made of

honeycomb cores with bonded graphite laminate skins and aluminum spars and ribs. The horizontal stabilizers use replaceable leading edges, as is used above, with corrugated aluminum substructure and riveted laminate skins with an aluminum root rib and shaft. The F-16 composite application has been simple and conservative.

The present composite systems have many limitations: they are susceptible to edge delamination; hole drilling and fasteners must be handled with great care to avoid local damage; and the systems are vulnerable to impacts. It is expected that next-generation aircraft will have more extensive composite application (40 percent to 60 percent) and be more complex. They will cover the exterior of the aircraft and be applied selectively for substructure. High-modulus fibers will be used. The contours will be complex and made from thin materials. Fuel tanks will use composites. The aircraft will require temperature-tolerant composites for operation at greater than $M = 2$.

The future technology thrusts need to be toward toughness for thin skins and larger panels to allow easier repair and maintenance and improved warranties. Toughness has not been easy to define because of design variables, the nature of damage, and the detectability of damage. The toughness issue is further complicated by the demands of manufacturing processes for flexibility, tolerance, and ease of manufacturing, including the ease of drilling, fastening, mating, and avoidance of local failures in forming.

Material properties that contribute to tough properties are strain critical energy release rates (G_{IC} and G_{IIC}), edge delamination strength (EDS), and incipient impact energy (IIE)—a set of interrelated properties. The test techniques used for determining these parameters do not, in most cases, represent real structures and thus do not always correlate well with full-scale test data. This issue needs to be examined.

An examination of where the technology stands and what is wanted regarding toughness indicates that the desired levels of toughness can be achieved. Thermoplastics have a role here. Proposed material properties are identified in Table A-2. In addition, the new materials need to have chemical resistance, repeatable processibility, machinability, lightning-strike compatibility, uniformity, and fatigue resistance.

In summary, experience to date is good but cannot be extrapolated; current materials are not good enough for projected high-performance aircraft; the nature of damage sources and progression needs to be identified; work needs to be directed at defining material properties that provide a good measure of toughness; and effort needs to be put into the development of tough composite materials—new thermosets may succeed and thermoplastics show promise.

The future for organic-matrix composites is bright. The factors that drive the interest in them are weight savings (performance gains), reduced part counts, reduced assembly time, corrosion resistance, and long fatigue life. A major obstacle is low tolerance to damage. Government and industry should place great emphasis on removing this obstacle.

TABLE A-2 Critical Material Properties Proposed for High-Temperature Composites

Property	Current Material System	Near-Term Material System	Target Material System
E_{11} (%)	1.1	1.3	1.3
E_{11} (MSI)	19.6	24.5	24.5
G_{12} (HOT/WET) (MSI)	0.35	0.35	0.35
T_G (WET) $^{\circ}\text{F}$	350.0	325.0	350.0
ρ (lb/in ³)	0.058	0.058	0.058
G_{Ic} (in-lb/in ²)	0.6	3.8	8.0
G_{IIc} (in-lb/in ²)	1.0	3.8	12.0
EDS (KSi)	28.0	35.0	120.0
IIE (ft-lb/in)	20.0	40.0	150.0

SOURCE: General Dynamic Corporation, 1986.

Northrop Corporation (R. S. Whitehead)

Designing with graphite composites does not present large, unsolvable problems. There have been 20 years of experience in their application. Their structural efficiency, fatigue resistance, and ability to withstand corrosion have been demonstrated. The technical problems are surmountable. Technical design matters and certification issues are understood and basically manageable.

The general experience is that composite parts are more expensive (per pound) to produce than aluminum and supportability of composite structures is poor. This aspect of design needs more attention.

With careful design, some of the critical certification issues can be resolved, i.e., temperature and moisture effects, material selection, fatigue and corrosion resistance, accelerated testing, and certification. However, work on the following matters is needed and very appropriate: out-of-plane failure modes, predication of full-scale structural performance, service durability of thin structures, and methodology to assess damage tolerance.

The matter of full-scale structural performance is especially worrisome. Most often, problems are not anticipated or understood until full-scale, complete aircraft

testing is accomplished. This applies to all classes of aircraft and is reflected in the fact that a significant number of full-scale test articles have failed (below design ultimate load) because of unanticipated failure modes. The major cause of these unanticipated failures have been out-of-plane loads. Analytical methodology is a vital need in this area. Of significant help would be dissemination of lessons learned from full-scale testing.

Northrop's experience in the production of F-18 (Hornet) vertical stabilizers (graphite epoxy) and F-5 (Tiger) stabilizers, when normalized, shows that the composite component is less costly than the aluminum structure (\$14,700 versus \$18,700). Composite material costs are greater (\$37/pound versus \$3/pound), but only 103 pounds, versus 135 pounds, of composite materials are used and labor hours are 90 for composites versus 158 for aluminum. These factors make a significant difference.

In addition to the high potential for reduced manufacturing costs, life-cycle costs should be reduced too. Cost reductions should accrue through lower weight, smaller aircraft, higher performance, excellent fatigue and corrosion resistance, and repair simplicity. However, the forenoted thin structures present problems related to edge damage, impact dents, punctures, handling damage, and moisture absorption. Lack of paint adherence is another annoying problem.

Future technology development with the potential for high returns are: improved manufacturing techniques to reduce acquisition costs; the improvement in operational maintainability and supportability (especially for thin surfaces) to improve operational readiness and lower life-cycle costs; and dissemination of lessons learned within the industry to minimize design and test process development redundancy. The government can be of considerable help here. NASA could do this job effectively.

Business Aircraft

Beech Aircraft (R. Abbott)

The health of the general aviation industry in the 1980s, compared with the 1970s, is poor both in number of units delivered and dollars of sales, especially when discounted for inflation. The pressure is on for industry to bring forth new high-performing products at reasonable prices. This is a matter of survival. Composites will play an important role.

The Beech Starship-1 is a response to this business condition. It represents a \$240 million investment. By late 1986, production buildup is projected to cost \$7 million per week. The aircraft structure will be about 70 percent composites (about 2,600 pounds of stiffened-skin composite construction).

The tools and facilities used for construction are adequate for conventional prepreg and autoclave application but cause high costs. Lower cost methods would be employed more extensively (resin injection, pultrusion, and filament winding) but for the lack of facilities and processes and of resources for their development.

The analytical tools used are considered adequate for design (laminate and finite element methods) but need refinement for certification work (laminate stability modes, very fine grid for local effects, and delamination). One matter of special significance is that current fatigue life analyses are not acceptable to the FAA. Other technical matters requiring attention include durability, environmental effects, variability, material stability, and defects including delamination.

The present data bases are not fully adequate for new designs. FAA circular AC20-107A (paragraph 6, page 3 and paragraph 7, page 4) illustrates the need for detailed attention to analytical tools to help minimize expensive, time-consuming, full-scale testing for certification. Published data bases (i.e., static and flaw growth compression and design strain-limit compression) are used for design followed by explicit company tests of materials under a range of environmental and damage conditions.

Adhesive bonding is employed for the wing. Bonding was chosen based on loads, allowables, weight, costs, and maintainability. Woven joint sections are used to bond skins to spars. High-load points are bonded and bolted through titanium and aluminum fittings.

Certification issues involve: damage detectability and damage-related ultimate-load design requirements; flaw growth and the scatter/threshold of stress; selection of environmental criteria for durability tests; proven techniques for laminate failure analyses; and quality assurance and safety of bonded joints. Beech has been involved in a dialog with the FAA regarding the documentation of material for the certification of bonded structures and their tolerance to flaws, environmental effects, and damage.

It is expected that at production rates, 18,000 pounds of graphite epoxy will be used per month. In more advanced designs, the material may not be graphite.

Work to date shows that: compression members are designed by the threshold of impact damage detectability (resulting in the lowering of operational stress levels to no-growth); "tool-proof" wing tests provide very useful data (compression stress concentrations, spar discontinuity, and incomplete torsion load path); and wet lay-up repairs during testing allow continued tests up to the point of failure.

When comparing composites with metals, experience shows that static compression (for damaged components) is critical compared to tension and fatigue, and that there is much greater scatter in flaw growth and life.

As others have found, composites have these advantages: lower airframe part count (King Air, approximately 8,000; Starship, approximately 1,700); lower cost and improved capability to tailor properties; lower weight; better contour control; and no corrosion. However, there are serious inhibitors to wider use: cost of manufacturing; lightning and related electromagnetic effects; certification cost and risk; and low bearing strength. Regarding manufacturing costs, labor is approximately \$4 per pound at present. Effort is directed at getting it to \$2 per pound.

The technical barriers to wider use of organic composites center around correlation to analysis, data variability, flaw growth, environmental tests and methods, and professional staffing.

Laminate analyses predict elastic properties, but they are inadequate for first

ply failure prediction of allowables of loads and stress because of material variability. Finite element analysis predicts strain and deflection but does not predict failure load, stability, or stress concentrations, nor does it handle incomplete load paths. However, the situation is about the same for metals.

Currently, static testing shows considerable scatter between lamina and laminate data. Durability testing requirements are uncertain. At present, test loads are designed to achieve two test lives. It is considered that this is equal to one service life. The FAA recommends and requires a statistically significant number of load cycles, but how many cycles is this? A B-basis at 10^7 cycles is used for threshold stress.

With regard to environmental testing, although present techniques are adequate they are time consuming and costly because of the large test matrix and the requirement for proof of thermal and moisture structural strain.

Adhesive bonding methods are available and have been successfully applied to joints, but it is clear from experience that surface preparation, quality assurance checks, and manufacturing care are needed. At Beech, a water break test is used for quality assurance of surface preparation. FAA has noted that it would prefer a direct method for checking the strength of each bond after processing.

General aviation has found it difficult to find individuals with combined aircraft design and composites skills. Most often the industry resorts to the hiring and training of new graduates. But when business is down, these people often are lost to the large, prime companies.

In summary, technology development is needed in areas related to manufacturing, analysis, and certification. In manufacturing, inexpensive methods for producing small composite parts (clips, brackets, and castings) to replace metal parts would be very useful. Stress on thermoplastics is needed to help clarify its place and value in future designs. Joint NASA/DOD effort in manufacturing technology development in these and other areas can have a large payoff.

Work on analysis methods, too, will have real payoff. Development of methods (and a handbook) addressing failure modes would be of specific value, i.e., stability, first ply failure, bearing strength, and flaw growth. Material characterization is an integral part of this effort and may well be the major issue. Joint sponsorship of university work by NASA and DOD is indicated.

Finally, regarding certification, damage tolerance guidelines for bonded structures are needed. The issuance of an advisory circular developed jointly by FAA and industry would be very useful.

Gulfstream American (H. Wardell)

The drive to composites for the Gulfstream IV was weight reduction. The aircraft has a typical metal structure with floor panels manufactured in-house and the following parts manufactured by others: rudder, ailerons, spoilers, wing trailing edges, forward and aft wing-body fairings, (nonpressurized) floor panels, horizontal and vertical stabilizer overhang panels, pressure bulkhead panels and beams, pylon ribs

and covers, and nacelle doors and fixed cowls. In time, most of this manufacturing will be moved in-house.

From this multiple exposure to composite designers and producers, it is painfully clear that no two parties do things alike. This has produced many problems from specification to acceptance testing for Gulfstream. All parties are aghast at what the others do:

- Require a minimum percentage of 90° plies versus no requirement.
- Re-cure versus co-cure of honeycomb skins.
- Redrying versus no drying of Nomex core.
- Tool selection variations, i.e., nickel, composite, aluminum, and matched dies.
- Requirements versus no requirements for environmental control.
- Kevlar considered a moisture barrier versus a moisture trap.

It was found that if designers did not work with the manufacturing groups it was necessary to redesign for manufacturing.

Gulfstream is building a composites facility (70,000 square feet—a \$6 million investment). The facility will have a bond room, autoclave room, quality control laboratory, a nondestructive-test section, and a trim room with appropriate current equipment for projected work. The composite activity has a staff of 60 that is projected to grow to 244 by mid-1987.

At present, for preliminary design, available industry data bases and analytical techniques are used. Tests to one lifetime are made in conformance with FAA AC 20-107A for primary structural lay-ups with maximum nondetectable damage.

The following are considered problem and inhibiting factors to broader use of composites:

- Lightning protection and knowledge related to expected damage and effective preventive design methods.
- Nomex core—environmental control requirements and their minimization.
- Honeycomb panels with 45° bevel angles failed much before panels with 25° bevels.
- Aluminum-core graphite-epoxy pans deformed in secondary bonding cycles due to thermal mismatch (Nomex did not).
- Parts inspected and passed by vendor or manufacturer being rejected by another even when inspected to same specification.
- Identification of the best standard test procedures and knowing or understanding what the results reveal.
- The need for the individual manufacturer to identify material allowables for specific systems and specifications.
- Identification of an acceptable corrosion barrier.
- No industry-wide set of composite fastener lists.

At Gulfstream, the lack of data bases on defects for such things as porosity, delamination, voids, and ply wrinkles inhibit wider use of composites. These factors directly impact production rate and cost. Another important fact, vendors and

outfitters lack the knowledge required to handle composites properly. Much more care is required than for metals in protecting the integrity of the aircraft when drilling for things such as mountings, attachment clips, and brackets for out-of-plant modifications.

The field could be helped by having: data readily available on manufacturing discrepancies (a comprehensive research effort quantifying effects, paralleling what is done for metals, would be helpful); feasibility studies for primary, intermediate, and nonstructural parts for varying design strain rates; studies of hole tolerance on fatigue strength; and studies to identify design strain parameters and values.

The larger companies can gather this class of data. The smaller companies are hard put to do the same. Yet, these kinds of data are required before a company can commit to full application of composites with low risk.

Airlines

Trans World Airlines (J. Janas)

These remarks relate to operational maintenance and experience, not design. Trans World Airlines (TWA) has had experience with composites on the 727 aircraft. Ultrasonic tests are used to check for debonding. Water ingestion is a common, relatively serious problem if the design is not proper. It leads to delamination, crushed cores, and out-of-balance trim conditions in flight. Other operating problems relate to the effects of oil and hydraulic fluid contamination and corrosion on structural integrity. TWA has also experienced delamination in noses of engine cowlings associated with the operating environment.

"Battle damage" is another general problem in civil operations. It is associated with ground crews, equipment, jet ways, hail, and other operational causes. Damage can be serious and costly to repair.

In general, there is low confidence in honeycomb because of water ingestion. There is also some concern about the crazing and cracking of Kevlar and associated structural integrity implications. Of special note is the need to replace about 60 windows per month on 747 aircraft because of crazing.

In the area of repair, temporary, airworthy repairs would be of great help. The ability to fly the aircraft back to the dedicated repair base or to continue in-service for limited periods can save an airline significant funds.

Nondestructive-testing techniques are needed to evaluate damage. For low-power x-ray equipment, there is a need to better understand what is seen on the picture and what it means. Airline operators need significant help in composite repair and maintenance.

Material Suppliers

Ferro Corporation (D. Forest)

Today the composite market for aircraft is dominated by fiber-woven fabrics, tapes, and rovings impregnated with resin. Good business data on the industry are

TABLE A-3 Composite Material Business Projection

	1977	1985	1990
Sales, \$million	80	350	1,000
Investment, \$million	20	400	650
Total employees	1,000	2,600	5,000
Professionals	400	900	2,000
Major competitors, worldwide	8	20	10
Number of products (approximate)	100	1,000	10,000
Lot size, average pounds	200	100	1,000
Market growth, annual percentage	20	15	10
Production capacity, pounds (million)			
Woven prepreg	13	18.5	30
Hot-melt tape	3	7.7	15
Roving	1	2.0	5
Capacity utilization, percent	60	35	70

SOURCE: Ferro Corporation, 1986.

not available, but within ± 20 percent, it is believed they can be characterized by estimates in Table A-3.

The market is relatively small, \$350 million, compared with the estimated value of the composite components generated, \$3 billion. Pertinent to the committee is the fact that an average of 3 to 5 percent of sales, some \$11 million to \$18 million in 1985, is applied to R&D by the material suppliers. Of this R&D, 70 percent is probably spent on direct product development. This leaves \$3.3 million to \$5.4 million for new product development. It seems clear that additional R&D investment is desirable from government and industry sources.

The number of products has grown and is projected to continue to grow; an effort is needed to reduce it. Profits in the business have been elusive and few firms have a return on capital investment of over 15 percent, not a particularly encouraging picture. Average pretax returns are about 5 percent. This low return can be expected to reduce the number of firms in the material supply business and can be expected to result in the development of fuller lines of activity within the remaining firms in the longer term.

From technology considerations, the user community has driven material performance up, i.e., stiffness, strength, toughness, and environmental resistance. Presently, these characteristics are considered good to excellent. Costs are low, relatively, for the materials used, especially if the lowest-cost material form is employed for a given job and is a small portion of the end-item cost. Quality from the consideration of reproducibility, tolerances, and material defects is a problem. Processes need to be statistically controlled. With adequate attention to detail, this can

be done; i.e., reduce costs of labor, rework and rejects, improve ability to automate user processes, and improve end-product performance reliability and durability.

Today most composite applications in aircraft are thermosets. It is projected that by the early 1990s thermoplastics will show a 20 to 30 percent utilization if: polymers are perfected that have a high level of toughness; prices are down from the \$100 to \$150 per-pound level to the \$15 to \$20 per-pound level; and high quality prepreg forms are developed. High cost may be the ultimate stumbling block.

Considerable development of equipment and techniques is also required to bring the thermoplastics state of technology up to that of thermosets. A possible hindrance is the large capital investment for materials processing required by manufacturers to utilize thermoplastics.

The costs of prepreg materials (fibers and resins) are 50 to 60 percent of the selling price. These costs are rising at 4 to 6 percent per year. Energy (for the incineration of polluting materials) is, at present, a major cost that can be reduced. The cost of obtaining and maintaining quality is high. Small lot sizes add to costs. Automation of production and quality control should help reduce material production costs as well as end-product costs.

Through positive action on these matters, prepreg prices should move down in the longer term. Actions to help assure that this happens include development of control laws and sensors for material processing and investment in new or improved processing and production equipment. The end user will have to be aware of and knowledgeable about the actions taken to have confidence in the product delivered and in how to use it. This will probably require sharing of data and work, matters not easily accomplished in a competitive environment.

It is important to note that there is excess material production capacity world-wide. If the need should arise, it should be relatively easy to increase capacity. Generally, the industry works one shift; it could work two. Further increases in capacity could take about a year, requiring the manufacture and installation of new equipment for material production.

In summary, it is recommended that: the government (NASA and others) continue to sponsor and/or conduct polymer research and technology development; the government continue to sponsor work to eliminate application barriers (proof-of-concept and demonstration programs) through teams/consortiums with matching industry funds; the government, principally DOD, support productivity improvement technology through industry consortiums and, in addition, permit the early recovery of plant and equipment investments; and universities give attention to teaching composite design and manufacturing and give industrial engineers credentials in composite process control and automation.

Union Carbide (T. W. Longmire, presented by C. Trulson)

Resins are a limiting factor in composites. Problems relate to control, testing, and qualification. There is a clear need for further intercourse and education among suppliers, designers, and fabricators.

Unlike metal systems, composites exhibit a broad range of properties that both complicate and make more flexible the attack on design problems. In composite aircraft, the structural characteristics of a final part or component depend not only on the material but also the manufacturing process. This interaction must be carefully factored into design and testing.

Experience shows that the qualification of a new prepreg material consisting of an approved resin and a new fiber takes some 9 months and costs an estimated \$60,000. Where the new prepreg is composed of a new resin and approved fiber, it is estimated that 20 months and \$1 million are needed.

There are four general issues from the suppliers' point of view: (1) test standardization, (2) prepreg standardization, (3) the use of thermoplastic matrices, and (4) education and communications.

Regarding test standardization, the material supplier is responsible for supplies that meet certain standards and tests to demonstrate to the user that the standards are met. Each user has his own standards. Standardization, among users, of sample preparation, testing, and data reduction would help reduce the number of tests required and speed the development of a common data base. The result should be to reduce costs for design and production and to reduce time for response to design requirements.

Because of the influence of manufacturing on component and system performance, unique component and system tests will still be required. But, even here there may be two test groupings: those that are essentially common between many applications and those unique to a given aircraft component and system. It would be helpful if the common testing were done by a qualified, mutually acceptable laboratory. This should accelerate the whole process of acceptance, design, manufacture, and application of common parts. The government could play an active role in the process through setting standards for specification and testing and publication of data bases, i.e., MIL Handbook 17, and the work of the Institute for Defense Analysis/American Society for Testing Materials (IDA/ASTM) on standard sample preparation and testing.

In testing standardization, these matters should form the basic set of tests: *generic* (unidirectional)—tensile strength and modulus, compression strengths, and transverse properties; *structural*—element tension and compression for open holes; and *damage tolerance*—compression after impact and edge delamination.

The prepreg standardization is an issue related to cost if cost indeed becomes a controlling consideration. Costs could be reduced through acceptance of a standard for prepregs in terms of width, thickness, and resin content. This would allow longer runs and reduce expensive preparatory labor per run. This would also reduce the amount of testing and scrap associated with start-up and shutdown. Prepreg standardization is an issue being addressed by industrial groups.

Broader use of thermoplastics hinges on increasing material toughness. It is reasonably evident that toughness can be improved by possibly an order of magnitude. For broad application, two issues need to be resolved: solvent resistance and fabrication technology. Both require active attention. For the first issue, requirements,

standards, and test procedures need to be established. For the second, as for thermosets, there is a need to move toward standardization of materials and material forms. If thermoplastics are to see early application, these matters need the early joint attention of suppliers and users. At present, 200°F to 300°F thermoplastic systems are practical but higher-temperature systems are probably not.

As has been noted, because of the influence of manufacturing on the characteristics of composite parts and systems, close communication between material suppliers and the user is needed. "Lightly structured" manufacturing technology programs could serve to accelerate innovative manufacturing technology development through joint supplier-manufacturer activity and produce the design data and handbooks required to extend and accelerate the application of composites. "Perhaps we would *all* know why bonded structures are held together by rivets."

Hercules (J. N. Burns)

It is projected that the strength of organic composites will continue to improve. Up until 1980, improvements were due primarily to better production technique. Since 1980, there has been a doubling in fiber tensile strength (400 KSI to the 800 KSI range) because of new product developments. Fiber tensile modulus has also increased from the range of 32 to 35 MSI to 40 to 45 MSI. These increases in performance indicate that it may not be wise to standardize.

Compression strength remains a problem that has not been resolved by the industry. Here, the matrix is an important issue. Composite compression strength has remained the same (in the 275 to 290 KSI range) while tensile properties have improved significantly. A near-term goal is an improvement of 25 percent (to about 350 KSI).

The price of carbon fiber has come down from a value of \$100 to \$6.99 per pound in constant 1972 dollars. In today's dollars, the price is \$20 per pound. Prices will go down a little further but a major change is not projected. State-of-the-art carbon fibers can be expected to stay in the \$17 to \$20 per pound range through 1990 with advanced carbon fiber moving down from a range of \$40 to \$65 per pound to \$25 to \$35 per pound. The cost per unit of strength and specific modulus for advanced composites (IM6 or IM7) should show an advantage over state-of-the-art products such as AS4.

The future of carbon fibers is promising in terms of improvement in strength. Carbon fiber modulus values should approach 50 MSI, and there should be reductions in price.

Resin improvements are a major objective for both commercial and high-performance military aircraft. Improvements in compression after impact (CAI) strength of 2.5 times state-of-the-art epoxies are being requested by prime commercial aircraft manufacturers. Military fighter aircraft requirements also request toughness improvements, but service temperature requirements in the range of 350°F to 400°F add to the difficulty of providing appropriate materials. Today's military fighter service temperature requirements are less than 300°F.

In 1985, a new thermoset resin (8551-7) was introduced having a CAI strength of 50 KSI, with a significantly reduced impact damage area. This area has gone from 3.5 square inches for 3501-6 to 0.40 square inches in 8551-7 with laminate damage contained in the first three plies of the CAI coupon exposed to 1,500 in-lb/in impact.

It has also been found that 8551-7 CAI strain is better in thermoplastics than in thermosets for a range of impact energies. At 2,500 in-lb/in impact level CAI strain is 0.7 percent for IM7X/8551-7 versus 0.6 percent for a thermoplastic versus 0.25 percent for a state-of-the-art epoxy. The 8551-7/IM7 has met the challenge of increased toughness without loss of hot/wet 0° compression capability at 180°F that was typical of early attempts to improve toughness.

Thermoset resins are meeting the toughness challenge and have an advantage of being able to use existing manufacturing equipments and techniques at both material supplier and aircraft manufacturing plants. The new material, in production quantities, is estimated to cost about the same as state-of-the-art epoxy preregs.

The graphite-fiber market for all kinds of products is projected to see a worldwide growth of some 20 to 25 percent per year through this decade. In 1985, the market was about 5 million pounds. The U.S. share was about half of this. Currently, the aircraft market is about 50 percent of the total U.S. market and is projected to grow to 60 percent by 1990.

Examination of the buildup of composite aircraft costs gives this relative per pound cost breakdown: graphite fibers, \$20; preregs, \$40; and structures, \$200 to \$500 per pound. The place to get major payoff for cost reduction is in structures manufacture, not direct material costs.

The challenges to continued composite application growth encompass: (1) material advances—toughness, temperature tolerance, compression strength, and reduced cost; and (2) finished structure cost—material manufacturability, automated-part manufacture, and product forms suitable for automation of processes.

Particular help is needed in the area of improvement in compression strength. Although it does not appear that basic material costs are a significant swing factor, the matter deserves attention from these two standpoints: (1) material consistency and (2) overspecification by end users.

Although thermoplastics were not specifically addressed in this commentary, they are receiving serious attention.

E. I. Du Pont de Nemours (J. K. Lees)

New material developments are moving rapidly. Regarding carbon fibers, increased stiffness and low cost are under study, as are new aramids. Compression strength is a problem that is being diligently pursued. Thermoset toughness is also being worked on as is a broad range of thermoplastics. Thermoplastics have their special place. Both "sets" and "plastics" will be employed in future aircraft.

The general outlook is for finished product costs to come down because of better fabrication techniques for materials and products and increased volumes of production.

There are a number of interesting thermoplastics in development: polyphenylene sulfide, polyetheretherketone polyamide-imide, and polyimides and polyamides. They are being examined in several product forms: impregnated yarns, impregnated-consolidated tapes, woven fabrics, and sheets. The selection of the best system will depend on the applications and manufacturing processes.

Growth barriers from an application sense include: costs for qualification (associated with the need to test finished structures); fabrication costs (lack of design experience and personnel); and cost and knowledge of fabrication processes (new materials with lack of experience, equipment, and personnel).

In general, qualification costs are a problem because of the need for large structural test specimens and limited ability to go (analytically) from material to small test specimens to actual structures. In addition, there is a limited ability to analyze designs for dynamic behavior and failure. A very high level of testing is dictated by these factors and the fact that materials themselves have significant variability, especially in their early development and production stage. Also, there is a lack of key property knowledge. All of this is compounded by process variability. The lack of standard and uniform test procedures also compounds the qualification cost picture.

Fabrication costs are driven by lack of material uniformity, process control, and material standards. In addition, costs increase through less than optimal use of materials, possibly due to the limited fundamental understanding of the composite materials and related design experience. The amount of off-line testing also can add significant costs. Material costs, themselves, deserve some consideration.

The introduction of thermoplastics has some of the older system problems. The technology must be used properly for success. Hardware development costs can be anticipated to be high and will require an integrated effort among suppliers, users, and equipment developers. If this new system is to be successful, a fundamental knowledge base needs to be developed.

Key to the future growth of composite application is the development of skilled personnel. The universities are beginning to help.

Regarding growth in composite utilization, the following essential points can be made: improve understanding and predictability—durability, dynamics, fatigue and failure, and large structures when going from test specimens; improve fabrication technology—nondestructive testing, joints, and resin processing; and increase training and education. Also of help would be designs that get away from “metal replacement” philosophies and practices.

It is recommended that NASA and DOD

- Encourage and support joint industry-academic programs that address fundamental scientific issues, performance predictability, and manufacturing science to reduce time for design and qualification;
- Assist in multidisciplinary programs to define and develop the technology for efficient manufacturing systems accounting for material forms, processes, and quality evaluation;

- Encourage cooperative industrial research;
- Reduce direct activity on new material development but not catalytic actions with industry; and
- Assist in vital training and educational activity.

COMMITTEE MEETING OF MARCH 26, 1986

Technology Needs and Budget

Table A-4 presents individual lists of the major research, technology, and development (RT&D) needs as viewed by the government representatives. Table A-5 presents the government's budget plans for advanced organic composite R&T.

U.S. Army (J. Waller)

A program level review of work on the following rotorcraft subjects was presented:

- Rotor-blade erosion protection;
- Damage tolerance and durability of primary structures;
- Fatigue methodology;
- Design criteria and analysis;
- Composite swashplate and hub design;
- Advanced Composite Airframe Program (Bell and Sikorsky, addressing landing gears, lightning protection, internal noise, repair and maintenance, crashworthiness, and weapon interfaces);
- Automated blade and low-cost fuselage production;
- Advanced fuselage tooling; and
- Single-cure, tail rotor blades.

Some specific points made are:

- In FY 1987 manufacturing technology activity has zero funding. It is the intent of the Army to build more capability in-house and phase-out contract work.
- There is a need for better materials for rotor blades to withstand rain and sand erosion.
- Manufacturers use a wide variety of methods for assessing fatigue that often give different results. This makes comparative assessments difficult for the Army. The same is true for damage and durability analyses.
- What is needed and is to be pursued (through in-house and contract activity) is the development of a design criteria "handbook" for rotorcraft. Issues related to thermoplastics have to be addressed and included too.
- Composite swashplate work is directed at a 15,000 to 20,000 pounds gross weight rotorcraft.

TABLE A-4 Advanced Organic Composite Research, Technology, and Development Needs--
Government View

<p><u>Army</u></p> <p>Design criteria (rotorcraft) handbook including crashworthiness</p> <p>Better rotor-blade materials to withstand erosion</p> <p>Consistent, repeatable, standard methods for assessing fatigue, damage, and durability</p> <p>Damage tolerance and durability criteria and design</p> <p>Ballistic and directed energy tolerance</p> <p>Simple, low-cost, field-level inspection techniques including nondestructive testing and quality assurance</p> <p>Repairability and maintainability with simple tools</p> <p>Reduced flammability and toxicity</p> <p>Decontamination techniques</p> <p>EMI/EMC avionics interference avoidance</p> <p>EMI and lightning-control techniques</p> <p>Cost reduction--materials, production, parts (count and size), repair and maintenance, and weight</p> <p>Improved materials properties</p>	<p><u>Navy</u></p> <p>Advanced design concepts:</p> <ul style="list-style-type: none"> high-strain primary structures Improved damage tolerant design methods <p>Thermoplastic and toughened thermoset structural components</p> <p>EMC design for composite structures</p> <p>Signature reduction</p> <p>Reduce complexity of repair and maintenance including time and cost</p> <p><u>Air Force</u></p> <ul style="list-style-type: none"> Increased attention to thermoplastics Decontamination techniques and processes--internal and external Simple, low-cost, rapid field repair and maintenance Techniques and processes for the manufacture of large parts <p><u>FAA</u></p> <ul style="list-style-type: none"> Detection of all classes of understrength bonds Fuselage impact damage containment Failure analyses Standards for materials testing including environmental effects Analyses techniques for complex load transfers Flammability, toxicity, and smoke characteristics Damage growth analyses Response to repeated loads Statistical analyses--reduction of mechanical testing Data scatter information--coupon vs. full-scale component tests Structural response, e.g., crashworthiness Design for protection against lightning 	<p><u>NASA</u></p> <p>System characterization:</p> <ul style="list-style-type: none"> mechanical properties, damage tolerance, micromechanics/failure, and environmental effects Structural concepts, efficiency, and tailoring Handling of gradients, discontinuities, cutouts, and damage Local and global structure analyses including failure mechanisms Postbuckling and nonlinear effects and analyses Subscale innovative modeling of wing-boxes and fuselage shells Filament-wound structures
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TABLE A-5 Government Advanced Organic Composite Research and Technology Programs

Agency	Funding (\$million)				
	FY 1985 (Actual)	FY 1986 (Plan)	FY 1987 (P r o j e c t i o n s)	FY 1988	FY 1989
<u>U.S. Army</u>					
Technology base					
Materials and manufac- turing technology	12.1 1.1	7.7 0.9	10.4 0.0	-- --	-- --
Total	13.2	8.6	10.4	--	--
<u>U.S. Navy</u>					
6.1 (Research)	--	0.25	0.3	0.3	0.3
6.2 (Technology development)	--	1.5	1.9	2.0	2.2
6.3 (Applied)	--	--	--	--	--
Total	--	1.75	2.2	2.3	2.5
<u>U.S. Air Force^a</u>					
Research and development	7.0	8.3	6.0	--	--
Supportability	0.2	0.5	0.9	--	--
Manufacturing technology	10.3	9.4	16.5	--	--
Structural concepts, integrity survivability, and repair	2.3	2.6	3.4	--	--
Total	19.8	20.8	26.8	--	--
<u>Federal Aviation Administration</u>					
Nondestructive inspection	--	0.1	0.1	0.1	--
Fuselage damage contain- ment	--	0.1	0.1	0.4	--
Structural response crashworthiness	--	0.1	0.1	0.5	--
Total	--	0.3	0.3	1.0	--
<u>National Aeronautics and Space Administration^b</u>					
Large structures programs funds	3.4	--	--	--	--
Advanced composites (R&T base)	2.8	2.9	--	--	--
R&T base	--	2.0	1.9	2.4	--
FY 1987 augmentation	--	--	3.0	3.2	--
Total	6.2	4.9	4.9	5.6	--

^aFunding does not cover salaries, metal-related work, or low observables.

^bFunding for research and technology (R&T) only; does not include personnel and overhead costs.

- The Advanced Composite Airframe (rotorcraft) Program (ACAP) is the first aircraft designed to all the requirements of military standard 1290, "Light Fixed and Rotor Wing Aircraft Crashworthiness." The program indicates that a 24 percent weight and a 24 percent cost savings over a conventional metal rotorcraft could be realized in an order for 1,000 aircraft.

- An advanced development program is under way on an advanced composite rotor hub. The rotor hub will be flight tested on an AH-64 Apache.

- A single-cure tail rotor blade design is estimated to save about \$700 per tail rotor and is being placed in production by Bell.

- Composite materials may need to be specified by the end-product buyer to allow reasonable control over design and related operations support. At present, each manufacturer uses the material it wants to use.

*Additional Comments** The technology needs for application of composite materials and structures for Army aviation are discussed in two categories (1) the specific needs related to military requirements for Army aviation, and (2) technology needs for aviation in general.

In Army aviation there are military characteristics that dictate particular requirements that affect composite structural design and technology needs for materials and structures. For Army aviation the needs are:

- Tolerance to various levels of ballistic threats. Generally, lower-level threats can be adequately handled in composite designs. It is high-level threats that present the challenge for innovative design.

- Tolerance to directed energy threats, both low- and high-energy, need to be considered in the design of composite structures.

- Repairability, maintainability, and capability are needed in adverse environments. Army aircraft operate in all types of weather, day and night, under battlefield conditions. It will be necessary to repair and maintain these aircraft without benefit of complex tools, equipment, and facilities. Repair techniques need to be developed that are simple, reliable, and easily performed with simple tools and limited access to electric or hydraulic equipment.

- Field-level inspection techniques and equipment need to be developed.

- Decontamination is a requirement prior to reentry to an uncontaminated area.

- Avionics issues related to electromagnetic interference must be addressed.

- Adequate techniques for handling lightning need to be developed.

The technology needs related to aviation in general are:

- Damage tolerance and durability are safety and life-cycle issues. Damage tolerance criteria need to be developed and validated. Programs are under way in the Army, Air Force, and Navy to provide preliminary criteria. Updating will be

*Submitted by J. Waller and R. Ballard after the March 26, 1986 meeting to amplify on Army activity.

required as more and more composites are introduced into the system. Durability, on the other hand, is an economic consideration. Criteria for durability need to be established for long-term operations in realistic operating environments.

- Crashworthiness designs are needed. The Army has been a leader in this area and has developed MIL-STD-1290a that identifies criteria for crashworthiness. ACAP is the first program that has required that the aircraft meet all the requirements of this standard. The design concepts used in ACAP will be verified by large-scale drop tests of static test articles in 1987. Crashworthiness is being considered by the other services and by the FAA.

- Impact and handling damage of composites needs to be accounted for in the initial design, taking into consideration attention to damage resistance.

- Cost reduction is a prime consideration. Efforts to reduce material cost need to be pursued for both material processing and volume production. More automated manufacturing techniques are needed. In designing composites structures the designer, materials engineer, manufacturing engineer, and the tool designer must work as a team. A reduction in total parts count and fasteners tends to reduce cost but there must be a trade-off on size. Large parts become difficult to manage and maintain. Although there are fewer fasteners used, the ones that are used are much more expensive than the "penny" rivet. Fastener cost must be reduced.

- Weight reduction is another key issue in the use of composites. Reduced weight produces cost and performance advantages.

- Improved material properties result in gains in strength: reductions in weight, cost, repair, and maintenance; and improvements in safety and survivability. Some of the properties of importance are tougher resins, higher strength, higher strain, and improved curing properties and damage tolerance. All these factors aid in reducing manufacturing cost.

- Better nondestructive-testing techniques for composites are needed for quality assurance in production as well as for field use.

- Flammability and toxicity characteristics for composites need to be documented and solutions to related problems sought.

U.S. Navy (D. Mulville)

The major thrusts of the Navy's composites research and development work (military categories 6.1, 6.2, and 6.3 related to research, technology development, and product development, respectively) were reviewed. The 6.1 work focuses on: developing a basic understanding of composite impact damage, fatigue, fracture, and innovative concepts for damage tolerant structures; composite structural tailoring; and metal structure crack initiation and propagation. The 6.2 work encompasses: advanced design concepts, structural integrity, supportability, air loads prediction, life management, and electromagnetic compatibility. The 6.3 work, not to begin until FY 1990, will be focused on thermoplastics, toughened thermosets, and advanced landing gears for Navy aircraft.

Some specific points are:

- About 50 percent of the 6.1 effort is on composites and one-half of this effort is with universities.
- About 60 percent of the 6.2 effort is directed toward composite technology. Due to budget reductions, out-year funding is expected to hold at \$2.5 million.
- The thrust of the 6.2 effort is to bring along the next generation of composites, i.e., introduce advanced design concepts for primary composite structures; reduce structural weight; increase tolerance to damage; and reduce complexity, time, and cost of repair and maintenance.

U.S. Air Force (J. Mattice)

The organic composites program consists of four major elements related to high-performance aircraft: (1) R&D, (2) supportability, (3) manufacturing technology, and (4) structural considerations. The first three elements of the program are directed by the Air Force Materials Laboratory and the fourth by the Flight Dynamics Laboratory at the Air Force's Wright Aeronautical Laboratory.

The major elements of each of the following programs were briefly described:

Organic Composites R&D

- Thermoplastics
- Thermosets
- New polymer concepts and resin characterization
- Processing science
- New composites technology
- Ordered polymer fiber
- Ordered polymer film
- Molecular composites
- Opto-electronic materials
- Support activity

Organic Composites Supportability

- Advanced field repair materials
- Post-failure analysis
- Paint removal
- Thermoplastic support

Organic Composites Manufacturing Technology

- Manufacturing science—computer-aided cure and complex shapes
- Integrated composite center
- Large composite aircraft
- Manufacturing for thermoplastics
- Radome manufacturing technology
- Composite repair center
- Organic propulsion materials

Structural Considerations

- Structural concepts

TABLE A-6 FAA Program Plans--Desired and Actual (\$million)

	Fiscal Year				
	1986	1987	1988	1989	1990
Desired program plan	1.9	3.9	3.9	3.7	3.2
Actual program plan	0.3	0.3	1.0	?	?
Shortfall	1.6	3.6	2.9	?	?
Actual Program Element					
NDI (nondestructive inspection)	0.08	0.10	0.10		
Fuselage damage containment	0.14	0.13	0.35		
Structural response	0.07	0.07	0.45		
Total (rounded)	0.30	0.30	1.00		

- Structural integrity
- Ballistic survivability
- Repair

Specific points made were:

- The level of funding identified for FY 1987 may not be realized.*
- The program outlined represents about 140 specific tasks (projects).
- Although work continues on thermosets, much of the effort is focused on thermoplastics.
 - About one-third of the program is directed at supportability.
 - Decontamination, internal as well as external, is a big issue and concern.
 - The ability to repair in the field is an important capability warranting more attention.
- The ability to manufacture large parts is a concern.

Federal Aviation Administration (J. Soderquist)

The funded (approved) R&T program and desired R&T program were reviewed. The program funding, noted in Table A-5, does not provide for the desired level of R&T activity. The shortfall is roughly estimated to be some \$1 million to \$2 million in 1986, and on the order of \$3 million to \$3.5 million in later years. These data and the actual program plan by element are shown in Table A-6.

Specific comments were:

- At present there is an active effort to increase FY 1987 support for the mechanical material property testing, large fuselage decompression studies, and

*See Table A-5.

repeated-load spectrum truncation work. How successful this effort to increase funding will be is unknown.

- In the plan, the budget numbers for the out-years are rough estimates that do not include resources for full-scale component work, which would be costly.
- Bonding integrity is an especially troublesome issue. A request for proposal (RFP) is in preparation and should be issued in FY 1987. It is directed at ways to examine or detect understrength bonds. This is a first-priority project.
- A second-priority continuing item of concern is failure analysis. There is also a real need to set standards including material property testing standards. Here it would be desirable to have NASA actively involved.
- Cost-effective finite element matrix analysis techniques are needed as is work to build a technology data base on fire-related material toxicity and other hazardous characteristics associated with a crash or fire.
- Damage growth analysis capability is also needed.

National Aeronautics and Space Administration (S. Venneri)

The budget (See Table A-5) and plans for advanced organic composites were reviewed in context with NASA's aeronautics R&T budget and program strategy. Major points made were:

- The funding for the advanced organic composites work in FY 1985 included residuals from the large-scale structures program that has been discontinued. The remaining FY 1985 funds come from the R&T base program.
- The approved NASA budget reflects a \$3 million augmentation for organic-matrix composites in FY 1987. However, if these funds do not become available, there will have to be a major reduction in the program. (It is possible that some funds could be restored through other internal adjustments.)
- The broad national R&D program goals focus R&T attention on the aerospace plane, subsonic transports (including rotorcraft), supersonic transports, and key military aircraft technologies.
- It is planned to increase NASA's total materials and structures (M&S) program (R&T base) from a level of \$30 million in FY 1987 to \$40 million in FY 1989. Organic-matrix composites work would decrease as a percentage of the M&S program in this time period.
- Composites, broadly, are to receive greater attention where they apply to national goals related to subsonic aircraft, rotorcraft, high-performance aircraft, and the aerospace plane.
- The FY 1987 budget outside of that related to advanced organic composites (See Table A-5) reflects an increase of \$10 million for materials and structures R&T related to: other composite materials program augmentation, increased computational structural mechanics effort, and R&T augmentation in rotorcraft noise and vibration.
- A NASA advanced composites program would encompass: structural concepts and sizing methodology for improved local stiffness and aeroelastic tailoring;

development and characterization of advanced composite materials; and component tests to verify design approaches to such items as panels, modules, and box and shell structures.

- NASA has outlined its views on "composite structure trends" and structured a program chart for "advanced wing/fuselage structure R&T"; an agreed upon program has not been identified so advice is very appropriate and useful.

- The budget outlook is such that it is expected that less contracting will be supported in the next few years due to increased internal costs.

Committee Summary of RT&D Needs and Budgets*

The committee's summary of the RT&D needs and budget plans as expressed by government representatives is presented in Tables A-4 and A-5.

Table A-7 is an integration of the views of the government's representatives on R&T needs by type of activity. The government representatives' views of important RT&D needs reflect those identified by the industry representatives.

Tables A-8, A-9, and A-10 display integrated budget data for FY 1986 and FY 1987 as a function of program element. From these tables it is clear that the major investment comes from DOD—some 86 percent; much of it is directed at system and manufacturing development technology (essentially an Air Force effort), which is considered critical to cost reduction. The NASA and FAA support, some 14 percent, is all directed to generic R&T. Although the NASA/FAA effort is shown as being funded at the same level in FY 1987 as in FY 1986, this will depend on the approval of a \$3 million NASA program augmentation.

In FY 1987, the Army plans to increase rotorcraft R&T funding, resulting in a significant rise in R&T funds. The Air Force has plans to increase its R&T support for design/support and materials/manufacturing activity. The combined result is an increase in overall program funds primarily for manufacturing technology.

The government (NASA, FAA, and DOD) has pursued opportunities for joint effort by identifying technology development opportunities in areas of common interest. Over the past 10 years this joint effort has produced significant developments in composites, including improved design and fabrication techniques, and in the basic production of advanced organic composite structural components. This type of work should continue, but at a higher (an order of magnitude) funding level to build the technology base required for design, production, test, and certification confidence, and to allow fuller application of advanced organic composites. Program detail must evolve from continued joint effort.

*This summary material was developed by the committee after the meeting on March 26, 1986.

TABLE A-7 Integrated Advanced Organic Composite Research, Technology, and Development Needs -- Government View

<u>Design</u>	<u>Test</u>	<u>Materials/Processes</u>
Damage tolerant, durable, efficient, tailored, crashworthiness design criteria and designs	Statistical analysis of test data to reduce mechanical testing	Improved material properties
Handling of gradients, discontinuities, cutouts, and damage	Assessment of data-scatter coupons vs. full-scale (large) tests	Better material--rotor blade erosion
Reduced avionics interference	Subscale wing boxes and fuselage shells to replace large-scale testing	Reduced flammability, toxicity, and smoke
and lightning control		Reduction of costs--materials, processing, and production
Weight control/reduction		Techniques and system for the manufacture of large parts
Ballistic and directed-energy tolerance		Filament wound structures
		Increased attention to thermoplastics
<u>Analysis</u>	<u>Repair and Maintenance</u>	
Techniques for assessments of fatigue, damage, and durability, including nonlinear behavior and post-buckling conditions	Simple, low-cost techniques and tools--inspection, repair, test, and quality assurance	
Techniques for analysis of complex, load-transfer structures	Techniques for detection of understrength bonds	
Analysis of responses to repeated loads	Decontamination, internal and external	
	Thermoplastic servicing	

TABLE A-8 Government Advanced Organic Composite Program
Plan, FY 1986 (\$million)

Government Agency	Program Elements			Total
	R&T	Design/ Support	Materials/ Manufac.	
Army (rotorcraft)	7.7	--	0.9	8.6
Navy	0.3	1.5	--	1.8
Air Force	8.3	3.1	9.4	20.8
FAA	0.3	--	--	0.3
NASA ^a	4.9	--	--	4.9
Subtotal	21.5	4.6	10.3	36.4

^aNASA augmentation request of \$3 million included.

TABLE A-9 Government Advanced Organic Composite Program
Plan, FY 1987 (\$million)

Government Agency	Program Elements			Total
	R&T	Design/ Support	Materials/ Manufac.	
Army (rotorcraft)	10.4	--	--	10.4
Navy	2.2	--	--	2.2
Air Force	6.0	4.3	16.5	26.8
FAA	0.3	--	--	0.3
NASA ^a	4.9	--	--	4.9
Subtotal	23.8	4.3	16.5	44.6

^aNASA augmentation request of \$3 million included.

Materials Manufacturing—Tailoring and Related Costs

Hercules (J. DeVault)

The presentation addressed fiber tailoring, prepreg tailoring, testing costs, and the state of activity and implications. It was noted that:

- Fiber strength is increasing and further improvements can be expected.
- Fiber stiffness is improving with more gains possible.

TABLE A-10 Government Advanced Organic Composite Program by Element, FY 1986 and FY 1987

Program Element	FY 1986		FY 1987	
	\$Million	Percent	\$Million	Percent
R&T	21.5	59	23.8	53
DOD	(16.3)	(45)	(18.6)	(42)
NASA ^a /FAA	(5.2)	(14)	(5.2)	(11)
Design & support (DOD)	4.6	13	4.3	10
Materials & manufacturing (DOD)	10.3	28	16.5	37
Total	36.4	100	44.6	100

^aIncludes NASA request of \$3 million augmentation.

- Material costs (\$ per pound) are still coming down for current materials and significant drops in cost can be expected for advanced materials with increased production volume.

- On the basis of unit price per modulus/density, advanced fibers are projected to be equal in cost to state-of-the-art fibers, and on the basis of unit price per strength/density, advanced fibers are projected to have a slight cost advantage.

- Higher filament count material has a lower cost.

- The factors affecting prepreg costs are: weight, resin content, width, and automatic tape-laying machine grade. Their effects are: (1) lower weight is more costly, (2) process cost increases with lower resin content, and (3) automatic tape-laying grade increases cost (compared with hand laying).

- Prepreg tow has the potential for being the lowest cost material form.

- Matrix tailoring will impact prepreg prices. Thermoplastics are projected to be priced in the mid-range of thermosets and both are projected to come down in cost. The types and number of tests per material lot affect costs. Holding tests down in production will hold costs down, but tests are a small part of the price structure (about 3 percent for fiber, 5 percent for prepreg).

- Increases in the number and types of tests being specified for new products result in higher materials costs.

In summary, as the field matures there is more tailoring of material. This has resulted in an increase in material costs. The suppliers are responding with improvements in manufacturing techniques to produce better products and hold costs down. This improvement trend holds promise for slowing the rate of cost increase. Costs may go from \$1/pound to \$2-\$3/pound. It is possible the number and/or frequency of testing could decrease with more production experience.

The Navy is selecting material specification and requiring two material sources.

In response, Hercules is working with Fiberite to produce specified material. This has required the complete transfer of related material processing and manufacturing technology.

It is believed that material-processing specifications can be tightened further (to ± 1.5 percent) resulting in lower handling/manufacturing costs for the user. It is believed that the materials manufacturers are working on the problem of material tolerances and that government assistance in this area is not required.

Logistic Support

Military service representatives from the Navy/Marine Corps, Air Force, and Army briefed the committee on field experience with aircraft composite structure repair and maintenance.

U.S. Navy/Marine Corps (J. Meyers)

Most nonstructural damage is reasonably handled in the field. However, structural damage is an issue requiring innovation and care and is generally not fully manageable in the field. As experience grows with composite repair and maintenance (R&M), information is being fed back to the manufacturers so that R&M is accounted for in design.

Techniques for obtaining three-dimensional "pictures" of hidden damages are being developed. These techniques show promise for internal damage diagnostics.

The basic problem for R&M is the ability to perform in-field work with limited support skills and tools. The Navy has developed a list of "future considerations" relating to what needs to be done and what can be done to improve field-based R&M.

U.S. Air Force (J. Harrington)

At the depot level, composite structure repair and maintenance can be handled reasonably well. But, there is concern about the ability to do the required work in the field. Of interest is quick, simple, effective repair capability. Supportability, related to R&M has been elevated to an important design-selection consideration. From a design standpoint, items of concern are damage containment and associated delamination and blowout. The service is also directing attention to standardization of approaches to and equipment for repairs.

An obvious major issue is quickly getting aircraft back into service, which points to the need for an effective field repair capability.

There is a renewed interest in honeycomb structures. This is due to an improved ability to eliminate surface microcracking, thus controlling moisture intake and avoiding delamination and internal metal corrosion.

It is forecast that in the next decade some 50 percent of the structural weight of Air Force advanced tactical fighter (ATF) aircraft will be composites. These

structures have to be supportable (in the field and at depots). Supportability requires design for inspectability, maintainability, repairability, and replacement. The enemies of supportability are environmental, service, and battle damage.

U.S. Army (T. Condon)

Major concerns related to composite structures are reliability, maintainability, and repair. Much of the noncombat problems are associated with work accidents, i.e., dropped tools and cart strikes. The Army has supported a number of studies directed at designing for inspection and R&M to reduce the impact of these problems. The philosophy is to consider R&M in design and design to allow field-level R&M. This approach must consider field skills and resources including limited environmental and quality control and such things as repair with dry materials and two-part epoxy resin, repairs with hand-formed metal parts, and modular repairs.

Some areas warranting future research and development include:

- Field repair kits;
- High-temperature materials repair;
- Generalized equipment for heat and pressure application;
- Portable nondestructive inspection equipment and techniques;
- Damage resistant and tolerant R&M design; and
- Damage assessment, test, repair, and retest.

These matters are to be addressed, to a degree, in an R&M program currently under development.

An Army-sponsored program developed inspection and repair techniques for a full-scale composite rear fuselage section of the UH-60 helicopter. This work has shown that with appropriate basic design, primary structure R&M can be handled in the field, but with some weight penalty. Repair kits need to be developed as do related heating and vacuum devices. However, there is a need for new personnel skills and training. Specifically, the R&M program found that: mechanical splicing was of high quality, repairs exceeded strength requirements, quality of repairs were verified by inspection, cosmetics were acceptable, and field repair was feasible.

Airline Perspective

The Kuperman/Wilson (United Airlines) report of 1977 detailed early airline experience with organic composite secondary structures.¹⁸ The committee was briefed on more recent airline experience. An update on airline views is contained in the Air Transport Association (ATA) letter presented in Appendix B.

Delta Airlines (C. Walker)

Weight saving is the interest that drives manufacturers and buyers to composites. However, safety, serviceability, and maintainability remain important considerations.

With honeycomb structures, serviceability and life have been serious problems. Surface cracking, water ingestion, delamination, sealants (resealing), and inspection are real concerns and problems. Stiffened graphite composite panel structure (rather than honeycomb) may be the way to go, but this may mean added weight. There has been limited experience with graphite in airline applications.

Other areas of concern for the airlines are fatigue resistance and damage growth. These factors are understood for metal structures but not well understood for composites, so for metals there is a high level of confidence. Much more experience is needed with composites to build the same level of confidence. Part of the problem is the need for good inspection techniques other than "coin banging."

The move to larger structures will bring forth problems of repair. What will be desired are repairable composites, designs that do not require special tools, skills, or support equipment.

The Kuperman/Wilson report still reflects the state of affairs today regarding the kinds of problems the airlines face with composites. However, the yearly operating costs associated with each pound of aircraft weight makes weight saving of serious interest and composites a competitive material. For a 727, \$18 per pound is the incremental cost of fuel; for the Delta fleet, incremental costs range from \$12 to \$24 for fuel per pound of weight per year.

Mr. A. Tobiason, of the ATA, invited guest of the committee, reported on recent environmental experiences with composite structures. A lightning strike on an aileron destroyed it and it took 5 days and 80 working hours to repair the aircraft at the airline maintenance center. On another aircraft, hail damage required the return of the aircraft to the manufacturer for repair.

Appendix B
Correspondence—Air Transport Association of America

Air Transport Association **ata** OF AMERICA

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December 19, 1986

Mr. Bernard Maggin
Aeronautics and Space Engineering Board
JH 413
National Research Council
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Washington, D.C. 20418

Dear Bernie:

The purpose of this letter is to provide you with further information for use in the NRC AD hoc Committee final report to NASA on the Status and Viability of Composite Materials for Aircraft Structures. At your suggestion, we asked several ATA member airlines to update the 1977 SAMPE paper^{1/}. As you will recall, three airlines have made earlier comments on the NRC study.

The airlines generally believe that notwithstanding efforts by the airframe manufacturers, their most recent technology transports are still showing problems that indicate any future R&D program recommended by the NRC Committee should include detailed attention to conditions experienced by the operators of new technology aircraft. The current list of problems is not much different from those discussed in the SAMPE paper. One way to put it is: can new technology reduce the overall cost-of-ownership? From listening to the DOD briefers who operate advanced aircraft which incorporate composite materials one would conclude that their operating and maintenance difficulties are similar to those of the civil operators.

Airlines operating the most recent domestic technology aircraft provided ATA with the following specific comments.

"We have observed the following problems in our present aircraft composite structure which are basically graphite/epoxy and graphite/kevlar/epoxy construction:

^{1/} "Today's Non-Metallic Composite Airframe Structure -- An Airline Assessment" by M. H. Kuperman and R. G. Wilson, of United Airlines.

1. Paint and resin matrix cracking leading to water ingestion and freeze/thaw delamination
2. Lightning strike damage
3. Inadequacy of aluminum flame spray lightning protection
4. Abrasion/erosion damage
5. Foreign object impact damage

We have observed these problems over a period of 4 years. We believe 3-5 years are sufficient to disclose operating problems pertaining to composite structure.

One general problem with composite panels is erosion of the leading edge on external panels. The worst erosion is seen on fan cowl doors, landing gear doors and wing leading edge panels. Erosion typically starts at the forward edge and extends back one quarter inch or more, involving several plies of material. If damage is not too severe, the panel edge may be smoothed by chamfering, then applying an epoxy resin to seal the exposed grain. A possible production improvement would be to wrap the edges of composite panels with a strip of fiberglass so that the end-grain is not exposed to wind and moisture.

Another problem inherent to Kevlar composite panels is water ingestion. Although we have had no discrepancies reported on one new technology aircraft to date, we do have experience on another new technology aircraft to draw from. Kevlar panels must be topcoated with a flexible polysulfide sealer to prevent water ingestion. Unsealed panels can ingest detrimental amounts of water after only 12 to 24 months in service.

Refinishing Kevlar panels previously topcoated with polysulfide sealer is another problem. It is difficult to scuff-sand the panel without sanding into the sealer. When this happens, the entire sealant coat must be sanded off. Sanding pads must be changed frequently since the sealer tends to gum up the pads. We did not want to use a sealant top coat in anticipation of the refinishing problem. However, in order to preserve the warranty provisions, we have continued to use the sprayable sealant topcoat.

Another potential problem with composites was discovered recently during our initial ultrasonic inspections of rudders and elevators using recommended procedures. The ultrasound signal was attenuated (absorbed) over much of the inspection area to the extent that the inspection could not be completed. The aircraft manufacturer recommended that we revert to visual and coin-tap inspections.

By design, composites tend to be dry (having the minimum acceptable amount of resin) in order to conserve weight. This may create tiny voids or air pockets which may attenuate an ultrasound signal and/or make the panel more susceptible to moisture ingestion and leading edge erosion. The composite ultrasound calibration standards provided by the manufacturer were manufactured with generous amounts of resin and yield excellent test reading. This particular comment points out the importance of establishing and maintaining quality control in manufacturing, which may be more difficult to achieve in composites.

In order to enhance future applications of composites, manufacturers should emphasize quality control, reliability and maintainability. Weight savings loses its significance if the structure cannot be maintained."

Another area mentioned by the airlines is the infrequent necessity, but costly in terms of the lost revenue, to ferry an aircraft from a field station to a major repair facility having appropriate capabilities to repair damaged composite structures.

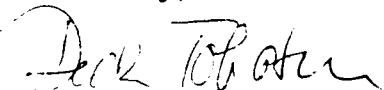
A previous ATA letter to you discussed some safety considerations worth examining in future R&D for use of composite materials in major fuselage and wing structures -- crash-impact dynamics and fireworthiness. As in other new technology areas, the excellent safety record of existing technologies should be maintained or enhanced, if economically possible. It is our understanding that the existing NASA composites program contains little, if any, specific safety content. On the other hand, the FAA has a limited safety program devoted to composites.

The NRC Committee may wish to consider a recommendation for development of a joint NASA/DOD/FAA-industry (manufacturers, vendors, airlines, DOD) program that encompasses pertinent maintenance and safety aspects in addition to performance objectives.

ATA member airlines appreciate NRC consideration of the above comments and request the opportunity to comment on future R&D endeavors the NRC may recommend on this subject.

Please let us know if we, or the ATA members, can be of further assistance.

Sincerely,



Dick Tobiason
Director - Engineering
Safety Technology

DT:jp